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THESIS

EVALUATION OF GEOMAGNETIC ACTIVITY IN THE MAD FREQUENCY BAND (.04 to 0.6 Hz)

by

Jeffrey Mark Schweiger

October 1982

Thesis Advisor: O. Heinz

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Evaluation of Geomagnetic Activity in the MAD Frequency Band (.04 to 0.6 Hz)

by

Jeffrey Mark Schweiger
Lieutenant, United States Navy
S. B., Massachusetts Institute of Technology, 1975

Submitted in partial fulfillment of the
requirements for the degree of

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from the
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ABSTRACT

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I. GEOMAGNETICS REVIEW

A. HISTORY OF GEOMAGNETICS

The beginnings of the study of geomagnetism lie back in prehistory when magnetic attraction between iron and certain minerals was first observed. Exactly when this phenomenon was first noticed is not known, but the properties of magnetite, then called lodestone, appeared in Greek literature around 600 B. C. (Brennan and Davis). [Ref. 1]

Chapman [Ref. 2] indicates that the directional property of magnets was known and used in Europe prior to 1200 A. D. and possibly in China before then. E. N. Parker [Ref. 3] noted "It is an interesting fact that the ancient walls of Peking were lined up with magnetic north rather than geographic north, a difference at that time of about 1°. We may presume that the surveyor found it easier to work with his compass needle by day than to sight on the pole star by night." This property allows the use of the Earth's geomagnetic field for navigational purposes.

By the mid-fifteenth century it was determined in Europe that the magnetic compass does not point to true north. The angle between true north and the direction indicated by the compass is now known as magnetic declination by the geophysicist and as variation by the navigator.

The magnetic field dip, or magnetic inclination is the angle, in a vertical plane, between the horizontal and the direction of the earth's magnetic field vector. It was observed in 1544 by an instrument maker in Nuremberg named Hartmann, and again by Robert Norman in London in 1581.

These discoveries or observations gave rise to the study of geomagnetics as a specialty which gained its cornerstone

with William Gilbert in 1600. After comparing his experimental results with the previous work of others such as Norman, Gilbert, in his book, "De Magnete," concluded that "magnus magnes ipse est globus terrestris (the earth globe itself is a great magnet)" [Ref. 2]. It is this concept, that the earth is itself a magnet, that is the basis of the science of geomagnetics.

Gilbert felt that the Earth's magnetism must remain constant except for geological changes, but it was soon determined that this was not the case. A 'secular variation' of the Earth's was found to exist.

Shorter term changes in the geomagnetic field were observed and it was eventually realized that geomagnetism is dynamic. In 1722 George Graham discovered that daily, or diurnal, variations exist [Ref. 2]. During the early Nineteenth century magnetic observatories began to be established to record the changes in the geomagnetic field in a systematic fashion (Knecht) [Ref. 4].

B. EARTH'S MAGNETIC FIELD

1. Constituents of the Geomagnetic Field

There are various ways of breaking down the constituting parts of the geomagnetic field. One way is to divide the field in terms of distance from the center of the earth. Doing this yields these three parts: internal, crustal, and external (AFGL) [Ref. 5]. The internal field originates in the core region and is the more stable field, containing only extremely low frequency temporal variations. The crustal (or anomalous) field arises from modifications made on the internal field by materials and structures in the Earth's crust. These variations are not spatially constant and give rise to some of what is known as geological

variations. The external field is the most dynamic and arises from many sources including the interaction between the solar wind and the terrestrial magnetic field.

Another way of describing the components of the geomagnetic field is by time variation. This division is accomplished by considering that part of the field which varies with periodicities greater than about one year as the _steady field_ and what is left as the _variation field_ (Knecht). [Ref. 4]

The steady field consists of the above named internal field, also referred to as the _main field_. Slow variations in the main field with periods of years or longer are referred to as _secular variations_.

2. _Models of the Main Field_

Various models of the main geomagnetic field make use of a geocentric dipole. Gauss, in 1839, demonstrated that, as a fairly good first approximation to the geomagnetic field, the field of a uniformly magnetized sphere (for points outside the sphere) is equivalent to the field of a magnetic dipole located at the center of the sphere (Jacobs). [Ref. 6]

The simplest of the present approximations of the geomagnetic field is that of a short bar magnet or dipole located at the center of the earth with an axis inclined approximately 11.5° from the Earth's axis of rotation. The sense of the field lines is from south to north (Figure 1.1).

The axis of this dipole intersects the earth at the geomagnetic north pole, 78.5°N, 291.0°E in geographic coordinates, and at the geomagnetic south pole, 78.5°S, 110.0°E. The moment of the geomagnetic dipole is 8.1×10^{22} amp-m². It is these poles that are used to define the geomagnetic

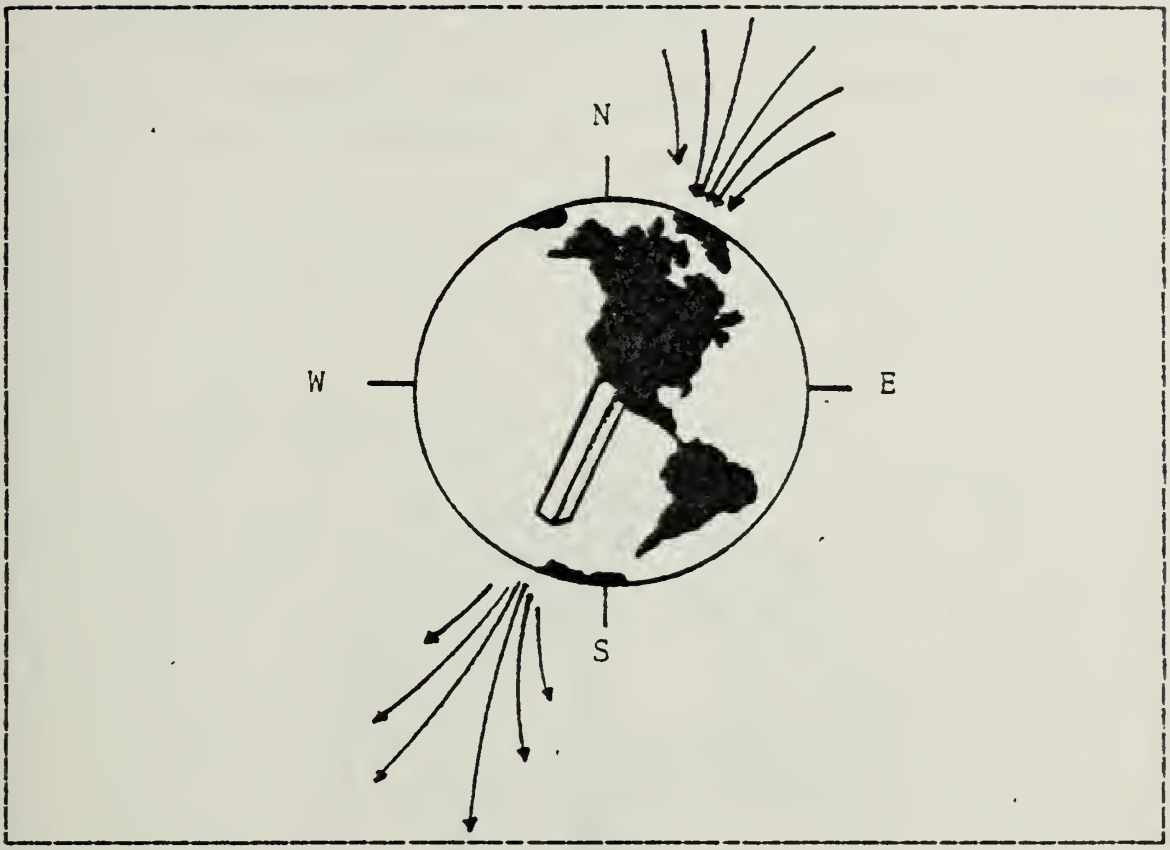


Figure 1.1 Dipole Appearance of Geomagnetic Field

coordinate system (Knecht) [Ref. 4]. The geomagnetic coordinate system is a spherical polar system similar to the geographic coordinate system with a geomagnetic equator defined 90 degrees away from either geomagnetic pole in latitude. This tilted geocentric dipole model describes the main geomagnetic field to an accuracy of about 10%.

In 1940 Chapman and Bartels defined an off-center dipole in the earth's interior, called the eccentric dipole. This dipole is displaced 0.0685 earth radii (436 km) in magnitude from the center and in the direction of the point 15.6°N, 150.9°E (geographic coordinates) (Vestine) [Ref. 7].

The intersections of the eccentric dipole axis at the earth's surface are 81.0° N, 84.7° W and 75.0° S, 120.4° E (Figure 1.2) (Haymes) [Ref. 8]. This approximation is accurate to within a few percent.

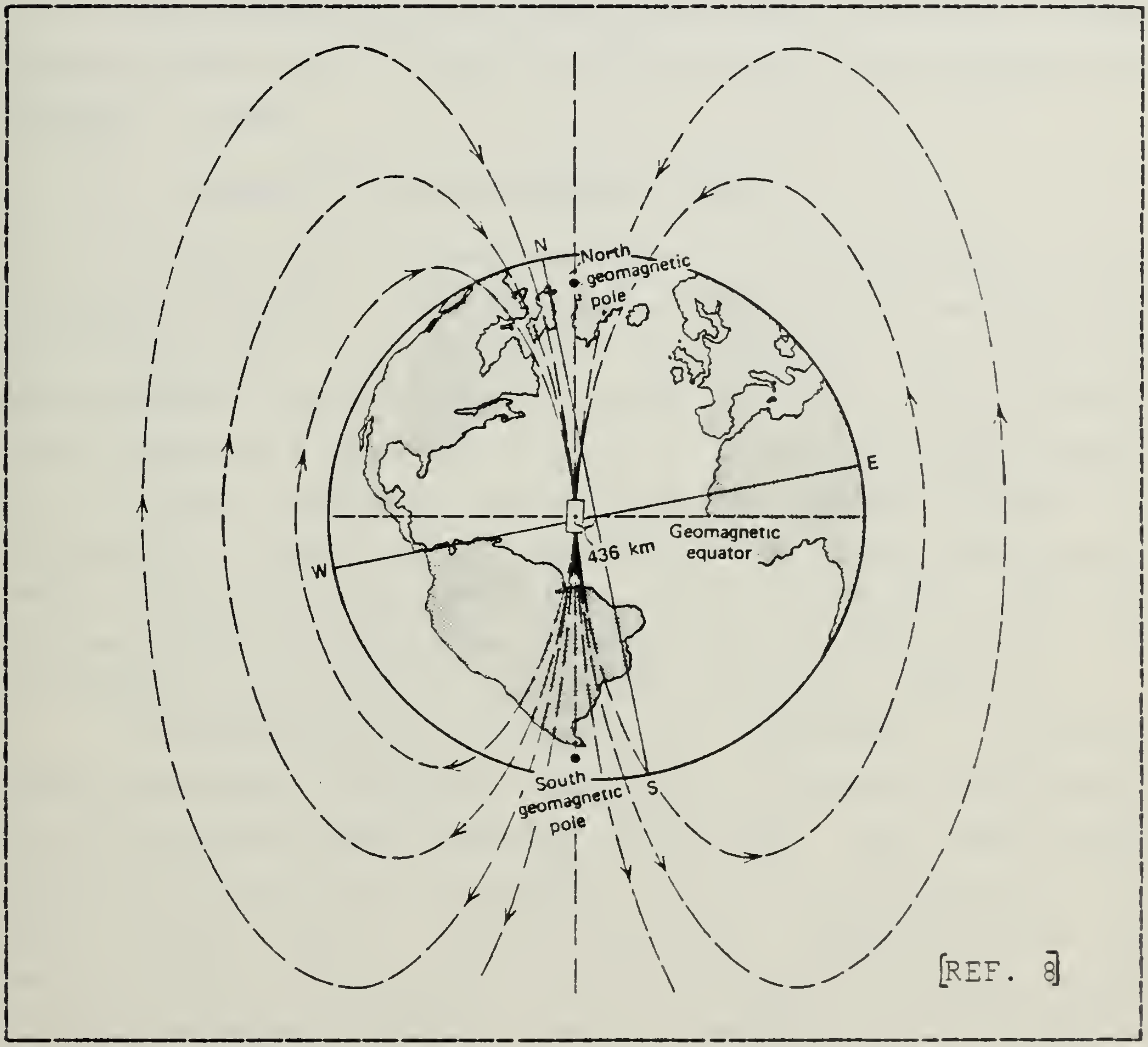


Figure 1.2 Eccentric Dipole Model of Geomagnetic Field

The field has additionally been modeled to an accuracy of about 1% by determinining Gaussian coefficients by a least-squares fit of experimental measurements of the

geomagnetic field. These coefficients are used in a spherical harmonic series representing the scalar potential of the field. This accuracy implies that the internal contribution to the total main field is at least on the order of 99%.

The International Geomagnetic Reference Field (IGRF) yields values which differ by only parts per thousand from measured values.

3. Sources of the Geomagnetic Field

There are various elements that contribute to the geomagnetic field, some external to the earth's surface and some internal. As previously mentionned, the external contributions make up only a small fraction of the steady field, playing a more important role in the variation field.

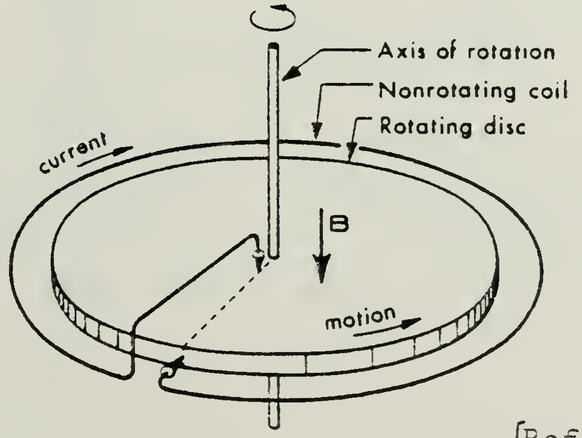
These external sources include current systems in the earth's upper atmosphere affected by solar electromagnetic radiation and gravitation, solar corpuscular radiation or the interaction of solar plasma with the main field, and the effect of the solar interplanetary field. [Ref. 4]

Various magnetic surveys of the world, including those conducted at ground level, by airborne instruments, and by satellite,have pointed to the fact that the largest source of the earth's magnetic field is internal to it. While there exists residual permanent magnetism in the earth's crust, this cannot be the principal internal source of the geomagnetic field due to temperature and material properties known to exist in the earth's interior (Nagata and Ozima). [Ref. 9]

Permanent magnetism is generated by microscopic electric currents, since a changing electric field will generate a magnetic field. Another way to generate a magnetic field is by the motion of electric charges in a

macroscopic current. Convective motion of the electrically conducting fluid core of the earth, resulting in a macroscopic current system, is considered to be the principal source of the main field.

The most promising present theory of the generation of the geomagnetic field is that of some sort of a self-exciting dynamo system. This means that the motion of a conductor, such as the molten iron in the earth's core, in a magnetic field produces a current which in turn induces a magnetic field in support of the original magnetic field [Ref. 4, 7]. A very simple model of such a dynamo is shown in Figure 1.3 .



[Ref. 4]

Figure 1.3 Simple Disk Dynamo

The original excitation or seed field may be due to an external field line, perhaps from the solar interplanetary magnetic field. This original, poloidal, field line is wound up due to the differential rotation (rotation not

constant with latitude) in the molten core. The wound up line becomes an intense azimuthal field which is carried outward by the upwelling associated with convection and twisted by the action of the Coriolis force. The twisting generates a helical toroidal field which, by outward diffusion, generates the externally observed quasidipole geomagnetic field.

The combination and interaction of two (see Figure 1.4) or more disk dynamos can also can also explain the reversal of the geomagnetic field [Ref. 7, 9].

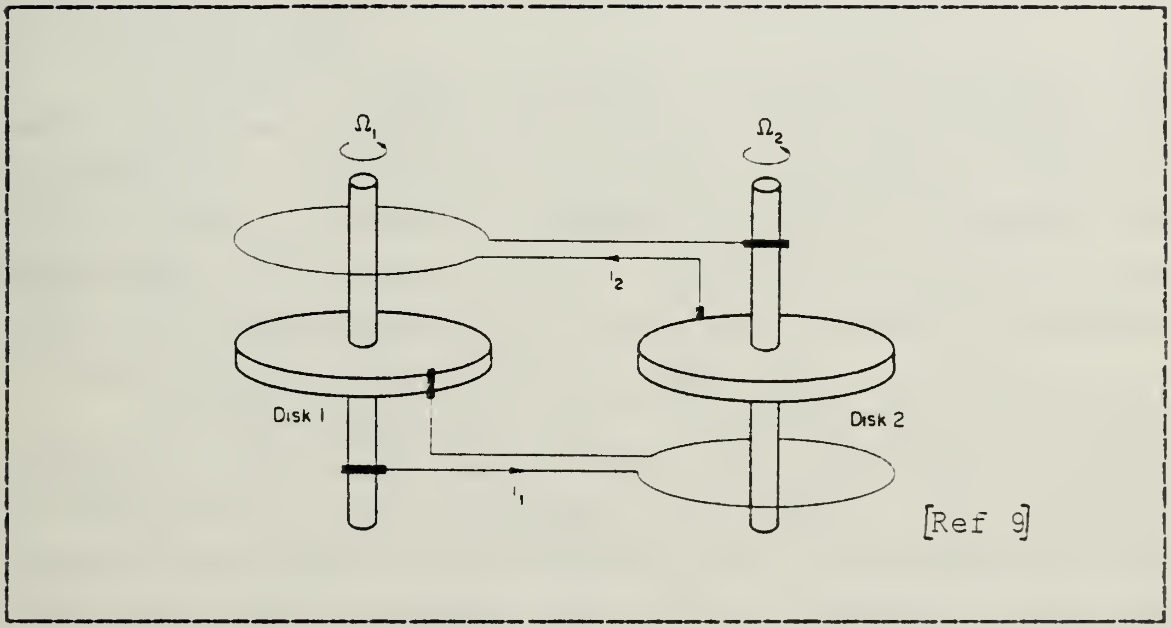


Figure 1.4 Twin Disk Dynamo

Regional anomalies that are nondipolar (do not conform to the dipole field) possibly arise from eddy circulations in the outer core [Ref. 4].

4. Magnetosphere

The **magnetosphere** can be defined to be that region (see Figure 1.5) occupied by the geomagnetic field above the ionosphere, a region where the field stongly influences the dynamics of ionized gas and charged particles (Kern) [Ref. 10].

If the space surrounding the earth were a perfect vacuum, the earth's magnetosphere and magnetic field might be more or less symmetric and extend outward until it merged with, and its strength became insignificant compared to the solar and other planetary magnetic fields. This turns out not to be the case.

Instead of being an island in a perfect vacuum, the earth encounters a continuous flow of hot, highly conductive ionized gas, or plasma, streaming outward from the sun. This continous stream of charged particles is called the **solar wind**. The density of this 'wind' near earth is on the order of 10 particles per cm^3, and has a velocity averaging 300-500 km per second (Jacobs). [Ref. 6]

Both the solar wind and the geomagnetic field exert pressure. The hot plasma of the solar wind pushes against the geomagnetic field deforming the field. At distances greater than about 13 or 14 earth radii, the pressure of the solar wind greatly exceeds that of the geomagnetic field and the geomagnetic field will be swept along with the wind. From 8 to 10 earth radii inward, the geomagnetic field pressure will predominate, excluding the solar wind, this being the region of the **magnetosphere**.

In the intermediate region, the magnitude of the solar wind and geomagnetic field pressures are comparable and the solar wind is compressed and flows around the geomagnetic field. This occurs when the magnetic energy density ahead of the plasma equals the kinetic energy

density of the streaming plasma. The solar wind is stopped at this point and forced to flow around the magnetosphere. This region where the magnetosphere starts is called the magnetopause. [Ref. 8]

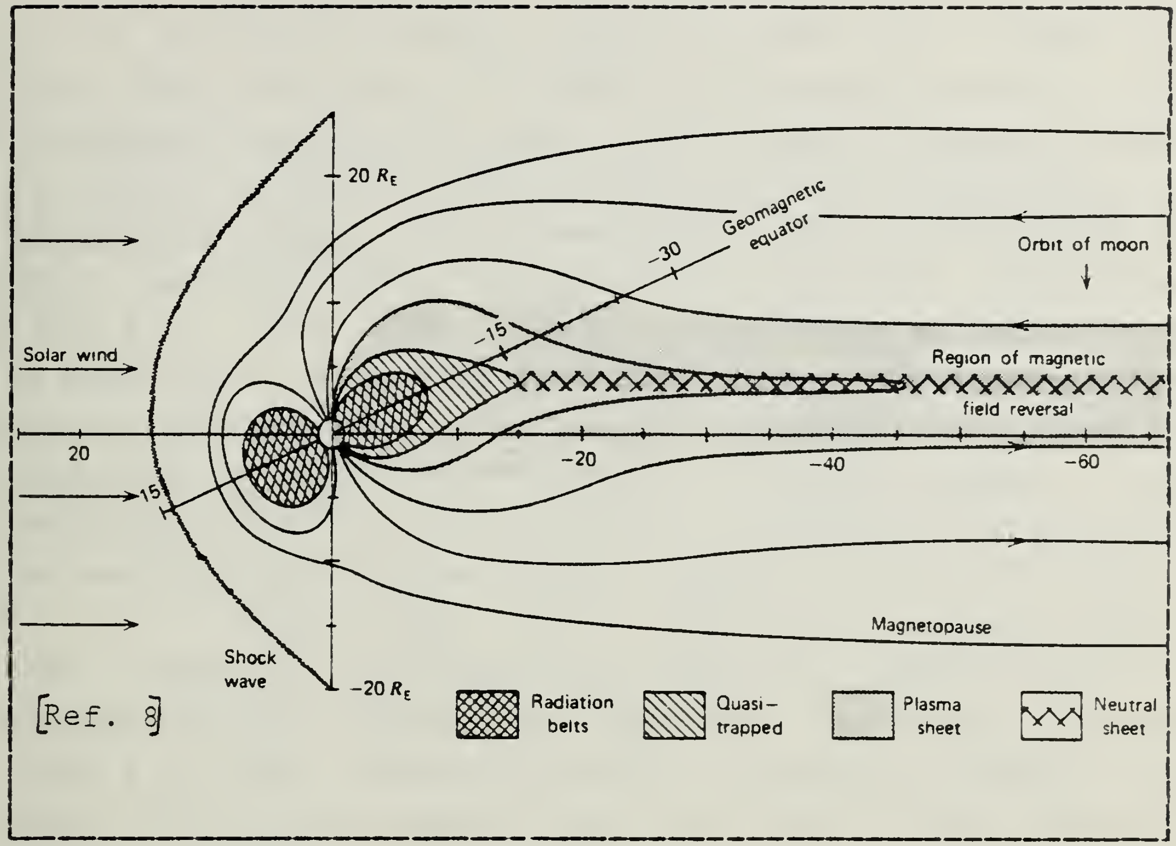
The velocity of the undisturbed solar wind is analogous to a 'supersonic' velocity. Thus a shock front is formed between the magnetopause and the solar wind. The magnetosheath is the region of severe turbulence that exists between the shock front and the magnetopause.

Since the solar wind always travels outward from the sun, the effect of the wind on the earth's main field is not completely symmetric, although it is almost symmetric about an axis through the earth and sun. A geomagnetic tail is formed where the wind sweeps the geomagnetic field along with it on the nightside of the earth [Ref. 4]. Figure 1.5 pictorially represents the effects of the solar wind on the geomagnetic field.

5. Time Variations of the Geomagnetic Field

The geomagnetic field changes with time. As previously mentioned, very slow variations in the main field with periods on the order of years to thousands of years are referred to as secular variations. Secular variations are geologic or 'paleomagnetic' in origin. Secular variations are not caused by a strength or orientation change of the center dipole. Paleomagnetic studies are used to determine the secular variation. Geologic structure, especially conductivity structure, may partially mask the secular variation at one point on the earth as compared to that at another point.

Other time variations of the field can be categorized into quiet variation fields and disturbed variation fields. Disturbed variation fields include geomagnetic



[Ref. 8]

Figure 1.5 Configuration of The Magnetosphere

micropulsations which will be discussed separately, since they are of particular interest as a noise source for MAD sensors.

a. Quiet Variation Fields

Quiet variation fields are those which are not due to disturbances in the interplanetary environment and which vary slowly and regularly [Ref. 4].

There are several contributing fields to the quiet variation. These include the *Solar Quiet Daily Variation* (*Sq*), the *Lunar Daily Variation* (*L*), and the daily variation due to magnetospheric effects.

The Solar Quiet (Sq) variation is the name given to the pattern of diurnal field variation with respect to solar local time which is caused by currents flowing in the ionosphere (Matsushita) [Ref. 11]. The major portion (about two-thirds) of the Sq field is due to what is referred as an **atmospheric dynamo**. High speed tidal winds are generated by solar heating causing convection of the upper atmosphere [Ref. 4]. These winds produce a stationary current system by moving the conducting particles of the upper atmosphere across the geomagnetic field lines. The daily variation is caused by the earth rotating under the current system. The remaining third of the Sq variation is caused by currents in the earth induced by the primary currents in the ionosphere.

The Sq field can be shown to be latitude dependent reaching a maximum at the magnetic equator where a concentration of current, the equatorial electrojet, exists [Ref. 4]. The maximum horizontal component intensity is about 100 nT at the equator with 25 to 50 nT more likely at higher latitudes.

Longitudinal, seasonal, and solar cycle dependencies also occur for the Sq field.

An example of the quiet-day variation at Monterey, California is shown in Figure 1.6 and is summarized in Table I. This data was taken using a Cesium Vapor total field magnetometer in February, 1979.

The Lunar Daily Variation, L, is approximately one-tenth the magnitude of the Sq field and exhibits a semi-diurnal behavior in lunar time [Ref. 4]. The major difference is that the winds are caused by lunar-solar gravitational tides. The L field is dependent on seasonal influences, lunar phase, the solar cycle, and latitude.

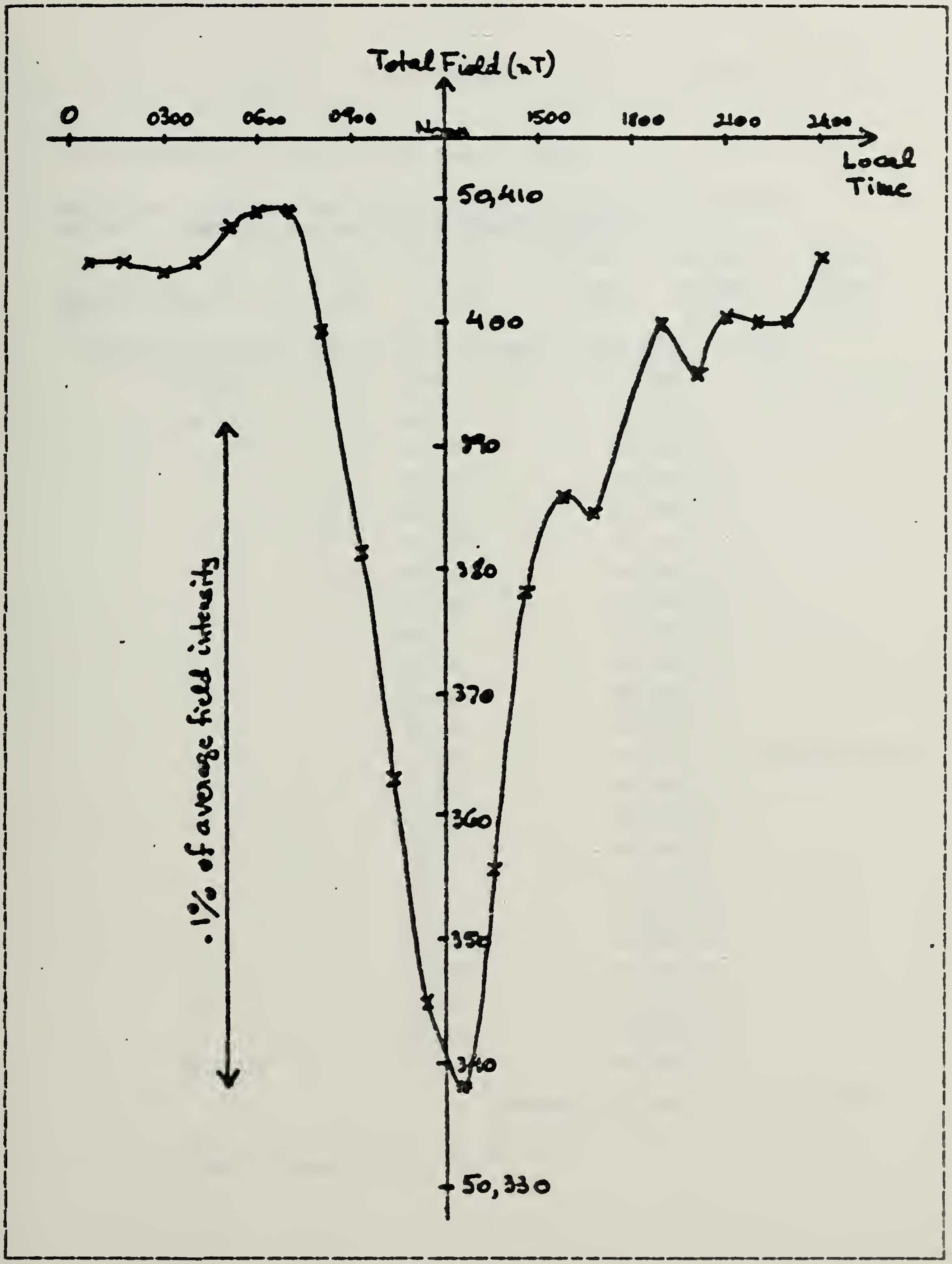


Figure 1.6 Variation of Total Geomagnetic Field Intensity, February 26, 1979

TABLE I

Quiet Day Variation in La Mesa Village, February, 26, 1979

POSITION 36°36'N, 121°51'W (LA MESA VILLAGE)

CALCULATED VALUES USING THE 1975 U.S. CHART MODEL (WORLD DATA CENTER A, BOULDER, COLORADO) FOR FEBRUARY 1979:

	D	I	H(NT)	Z(NT)	F(NT)
VALUE (FEB. 1979):	15.96°	60.74°	24,650	44,007	50,441
YEARLY CHANGE :	-2.3 '	- .8 '	-4.3	-32.1	-30.1

MEASURED VALUES OF TOTAL FIELD INTENSITY FOR FEB. 25, 1979

DATE	TIME	F(NT)	
2/25/79	00:44	50,405.24	
	01:48	50,405.79	
	02:52	50,404.80	
	03:56	50,405.48	
	05:00	50,408.19	
	06:04	50,409.15	
	07:08	50,409.66	
	08:12	50,399.69	
	09:16	50,381.59	
	10:20	50,363.68	
	11:24	50,345.08	
	12:28	50,338.51	MID-DAY LOW
	13:32	50,356.48	
	14:36	50,378.86	
	15:40	50,386.98	
	16:44	50,384.30	
	18:51	50,400.81	
	19:55	50,396.91	
	20:59	50,401.85	
	22:03	50,400.80	
	23:07	50,400.54	
2/26/79	00:11	50,406.51	

AVERAGE 50,390.50 ± 21.43 (NT)

$F_{CALC} - F_{MEAS}$ = 50.5 NT OR .1%

A diurnal effect due to the dayside-nightside difference in compression by the solar wind of the geomagnetic field causes a small variation of the order of 3 nT [Ref. 4].

b. Disturbed Variation Fields

Disturbed variation fields are geomagnetic field variations that appear to be the result of interplanetary environmental changes and do not possess a simple periodicity. These variations include ionospheric disturbances, the aurora, geomagnetic storms, and geomagnetic micropulsations.

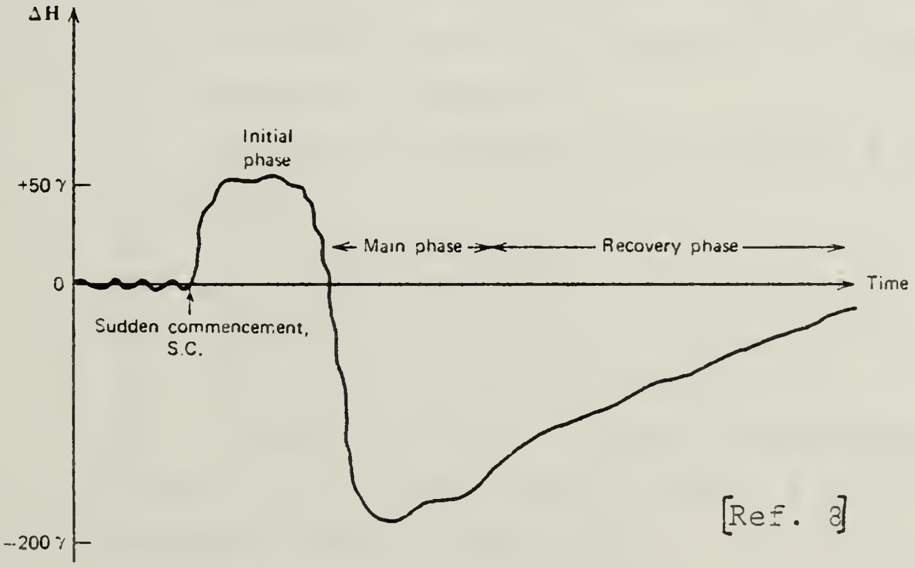
An ionospheric disturbance is a departure from the normal behavior of the ionosphere.

Solar flare effects (SFE) are magnetic disturbances produced by X-rays emitted from the solar flare. SFE's usually have a rapid onset, typically a few minutes in duration, followed by a slower return to normal. The entire event lasts on the order of an hour (Reid). [Ref. 12]

Auroras are caused by the precipitation of charged particles down magnetic field lines into the atmosphere and can be one of the brightest visual phenomena in the sky. The more intense and active auroras occur with geomagnetic disturbances and greatly increase ionization as well as creating the spectactular visual displays. [Ref. 4]

Geomagnetic storms are due to a change in the dynamic pressure of the solar wind. A typical storm begins with a compression of the magnetic field by an increase in solar wind dynamic pressure called a sudden commencement (SC), which increases the magnetic field (The so-called "gradual storm" begins with a gradual increase in field strength). The increase in field strength is on the order of several tens of nanoTeslas (nT) and takes about one to

six minutes to rise. If a disturbance starts with an SC but lacks the succeeding stages of a storm it is referred to as a sudden impulse (SI). Following the SC, the field remains compressed for two to eight hours in the initial phase of the storm. The main phase follows the initial phase. Over a period of hours to a day a westward ring current is set up at a distance of several earth radii whose magnetic field leads to a decrease in field strength on the order of 100 nT. This decrease overshoots the equilibrium field strength and leads into the recovery phase of a day or longer where the field returns towards its prestorm strength as the ring currents gradually dissipate [Ref. 4], (Matsushita) [Ref. 13]. A magnitude-time graph of a typical geomagnetic storm is shown in Figure 1.7.



[Ref. 8]

Figure 1.7 Typical Midlatitude Geomagnetic Storm

Geomagnetic micropulsations are rapid fluctuations in the surface magnetic field with periods of about 0.2 seconds to 10 minutes (frequencies about 0.0016 to 5.0 Hz). These are observed as a type of geomagnetic disturbance by ground based magnetometers [Ref. 4]. Micropulsations will be discussed in depth later.

6. Elements of the Magnetic Field Vector

The geomagnetic field vector is measured or characterized at any point by its direction and magnitude. This can be done in terms of some set of three independent parameters such as two direction angles and the magnitude, or three perpendicular components. [Ref. 4]

The system of coordinates commonly employed for describing the geomagnetic field on the surface of the earth is shown in Figure 1.8. The field is measured in terms of local (geodetic) coordinates with respect to True North.

The various coordinates are referred to as magnetic elements and are defined as follows:

B: Total Field Intensity (the symbol F is also used)

H: Horizontal Component

X: Northward, or North-South Component

Y: Eastward, or East-West Component

Z: Downward, or Vertical Component

D: Declination or magnetic variation. This is the angle between X and H and is measured positive eastward.

I: Inclination or dip angle. This is the angle between H and B and is measured positive downward.

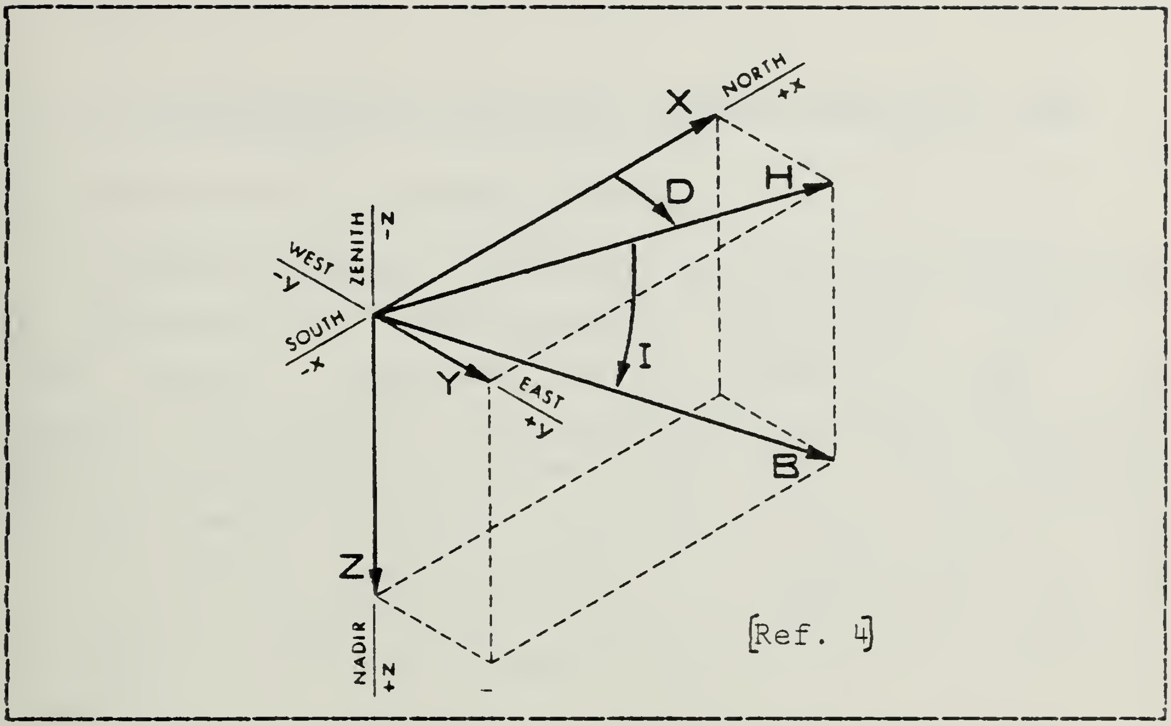


Figure 1.8 Magnetic Field Elements

II. INTRODUCTION TO MAGNETIC ANOMALY DETECTION (MAD)

A. DEFINITION OF A MAGNETIC ANOMALY

A magnetic anomaly is defined as any spatial variation or disturbance in the geomagnetic field which is due to local causes. Anomalies can be caused by waves, ore deposits, sea mounts, and magnetized objects such as surface ships and submarines (Anderson) [Ref. 14]. For the purposes of this research, magnetic anomalies due to a simple dipole field, such as those generated by submarines, will be regarded as signals, while other anomalies will be regarded as noise and will be discussed later.

B. HISTORICAL DEVELOPMENT OF THE MAGNETIC DETECTION OF SUBMARINES

1. Early Detection Systems

Attempts at finding submerged submarines by sensing disturbances in the geomagnetic field date back as least as far as World War I. In 1918, Earnest Merritt, at the Naval Experimental Station, New London studied the use of a fixed coil type of detector for use in moving boats and airplanes (Slichter). [Ref. 15]

MAD, originally known as Magnetic Airborne Detector, and now called Magnetic Anomaly Detection, had its beginnings as an airborne ASW sensor in late 1940 and early 1941.

Anomalies in the geomagnetic field caused by the presence of submarines, are on the order of one to a few nT (gammas) in magnitude. This is quite small compared to the magnitude of the field itself (30000 - 60000 nT). Two methods are generally employed to measure this small

disturbance. One is to use a gradiometer which measures the spatial rate of change of the magnetic field or its gradient. The second method, and the one presently used by U.S. Navy aircraft is to use a magnetometer to directly measure changes in the magnitude of the magnetic field.

The British investigated the use of a gradiometer for submarine detection, and by early 1941, had developed a two-coil gradiometer system which could detect a submarine at a range of 200 feet under favorable conditions. This range was considered to be too small to be of operational value and work on such a system was terminated when a magnetometer system showed promise (Coleman). [Ref. 16]

By late 1940, Victor V. Vacquier of the Gulf Research and Development Company had developed a sensitive saturable core magnetometer intended for geophysical (mineral) prospecting. The Vacquier magnetometer became the basis for further MAD development. The Airborne Instrument Laboratory of Columbia University continued the investigation of means of localizing submerged submarines by MAD.

The simplest saturable core or fluxgate magnetometer consists of a saturable or ferromagnetic core around which a coil of wire is wrapped (see Figure 2.1). This coil carries a sinusoidal current, I(t), which is large enough to saturate the core during part of each cycle. The inductance of the coil will change as a function of the magnetization of the core. The core magnetization, in turn, depends on the instantaneous current in the coil, and, if present, the external magnetic field.

In the absence of an externally applied magnetic field, magnetization as a function of exciting current is symmetric around I=0 (Figure 2.2). An external magnetic field parallel to the core's axis will change the magnetization of the core and shift the magnetization curve. This

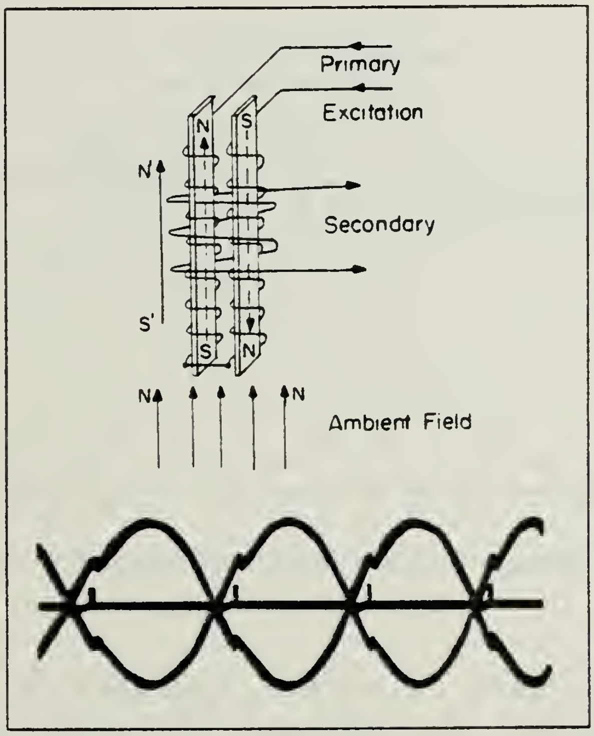


Figure 2.1 Element of Fluxgate Magnetometer

change will cause an asymmetry which can be sensed by analyzing the harmonic content of the signal. The coil can be combined with a stabilizer system, which keeps the detector element (coil) aligned with the geomagnetic field.

This was the basis of the MAD magnetometers used in World War II such as the AN/ASQ-1, ASQ-1A, and ASQ-2 [Ref. 16].

The fluxgate magnetometer measures only the component of the external field parallel to the axis of the ferromagnetic core. In order to measure the total field in this fashion it is necessary to align the ferromagnetic core along the earth's magnetic field or by using mutually

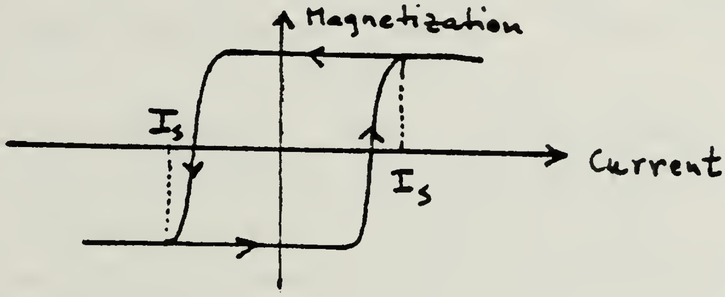


Figure 2.2 Magnetization Versus Exciting Current

perpendicular (orthogonal) cores. Precision requirements made this type of system difficult to realize during World War II but it has since found many years of operational usage and has found widespread use in geophysical exploration work and satellite mapping of the geomagnetic field.

2. Early Operational Usage

During World War II MAD provided a passive method of detection and tracking of submerged submarines. Within its range (then on the order of 500 feet) MAD gave a measure of surprise to the attacking aircrew. Until the first attack was delivered the crew of the submerged submarine might not even be aware of the aircraft hunting it.

Operational deployment of MAD began on a limited basis in December, 1941 with the installation of the early Mark I MAD in a blimp at Naval Air Station Lakehurst, New Jersey [Ref. 16].

By the end of 1942, MAD was operational on board PBY Catalina aircraft, nicknamed "Madcats." Even though MAD was operational at this time, it was not until February, 1944 that an initial contact by MAD led to the sinking of a submarine.

During February, 1944, the Madcats of Patrol Squadron 63 were assigned to fly a MAD barrier patrol of the Straits of Gibraltar. On 24 February 1944, a Madcat of VP-63 detected U-761 by use of MAD and commenced tracking to confirm the contact as a moving target. An attack was conducted in conjunction with another Catalina, two destroyers, and eventually two other aircraft, and U-761 was sunk. U-392 was sunk after a similar MAD contact on 16 March, and on 5 May, the third successful attack on a U-boat resulting from an initial MAD contact took place when U-731 was sunk (OEG No. 51, Price). [Ref. 17, 18]

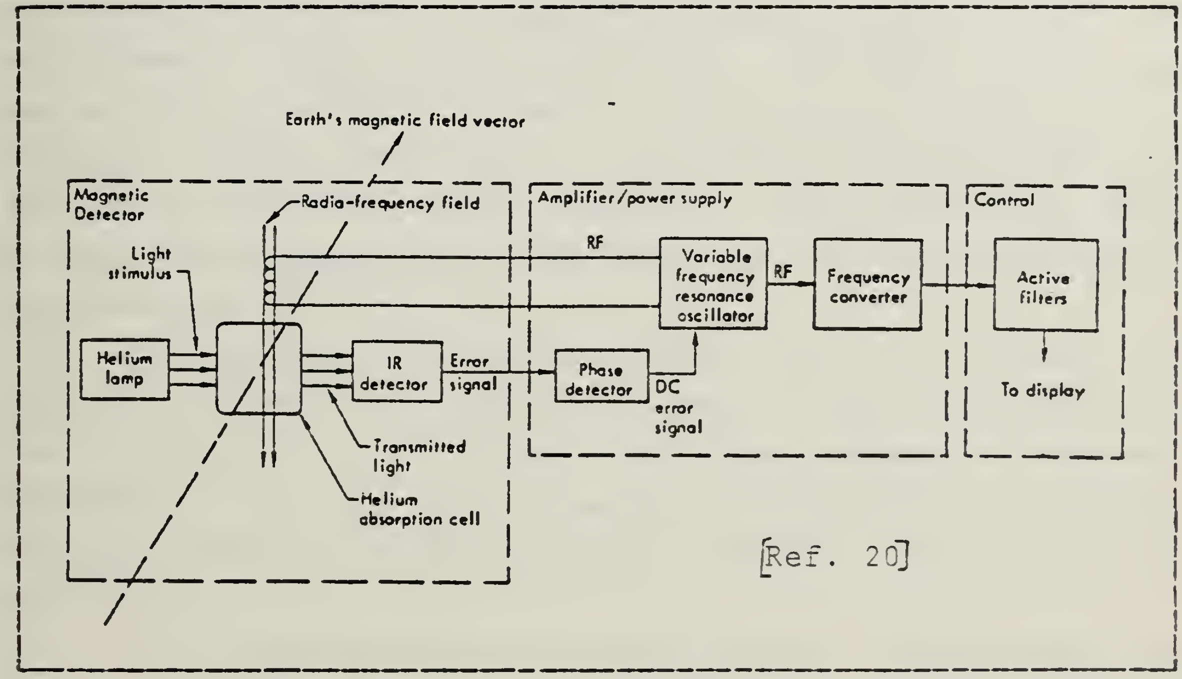
The attacks at the Straits of Gibraltar demonstrated that though MAD has a limited search rate, there are scenarios where it can be employed effectively as a search sensor, such as providing a blockade across a restricted area without the presence of surface craft (OEG No. 54) [Ref. 19].

3. Current Systems

The magnetometer system in current operational use is the optically pumped magnetometer. The optically pumped magnetometer measures the external magnetic field by making use of the fact that when an atom is immersed in a magnetic field, its energy levels are split. This is known as the Zeeman effect. For the fields of interest, the amount of splitting of the levels is proportional to the intensity of the magnetic field. By measuring the separation between the levels the magnitude of the magnetic field can be determined.

This type of magnetometer usually makes use of Cesium or Rubidium vapors, or Helium gas. The current operational MAD system, the AN/ASQ-81, is a Helium gas optically pumped magnetometer.

In an optically pumped magnetometer (see Figure 2.3), the sample vapor or gas (such as Helium) is collected into an absorption cell. Circularly polarized light is passed through the cell giving up some of its energy in exciting or pumping the electrons of the sample gas to higher energy levels. These electrons then fluoresce to lower, metastable energy states. This is 'optical pumping.' A detector monitors the degree of optical pumping by measuring the transparency of the gas cell.



[Ref. 20]

Figure 2.3 Metastable Helium Magnetometer

The actual separation of the energy levels is measured by applying a weak R. F. field which redistributes the

electrons among the ground state sublevels. These transitions will only occur when the R. F. field has a particular frequency (called the Larmor frequency) which is proportional to the separation between the levels and therefore to the external magnetic field [Ref. 20]. Thus measurement of this frequency yields a direct value of the magnetic field.

4. Future Developments

Optically pumped magnetometers are the most sensitive sensor for fleet usage today. Increasing capability to make use of the phenomenon of superconductivity will yield more sensitive MAD sensors. Superconducting Quantum Interference Devices (SQUIDS) which make use of the Josephson effect have a theoretical sensitivity of 10^{-7} nT as opposed to the theoretical value of 0.001 nT and the operationally realized value of 0.01 nT in current fleet systems (Chilton) [Ref. 20]. Field changes on the order of 10^{-5} nT have actually been measured. This SQUIDS are used in both superconducting magnetometers, and superconducting gradiometers.

A Josephson junction consists of a thin layer of insulator between two superconductors. This junction has the property that a current can flow across it without developing a voltage up to some maximum current. A voltage is developed for all current values greater than the maximum current.

In a superconducting magnetometer a superconducting ring containing a pair of Josephson junctions is used to measure the amount of magnetic flux penetrating the loop. This system is a vector magnetometer which measures variations in only one field component.

By using more than one superconducting loop, it is possible to measure magnetic field gradients, and construct a superconducting gradiometer. This is also a component, or vector, sensor.

These instruments have been used extensively in the laboratory and to some extent in geophysical work, but considerable engineering problems remain to be solved before operational Navy use can be contemplated.

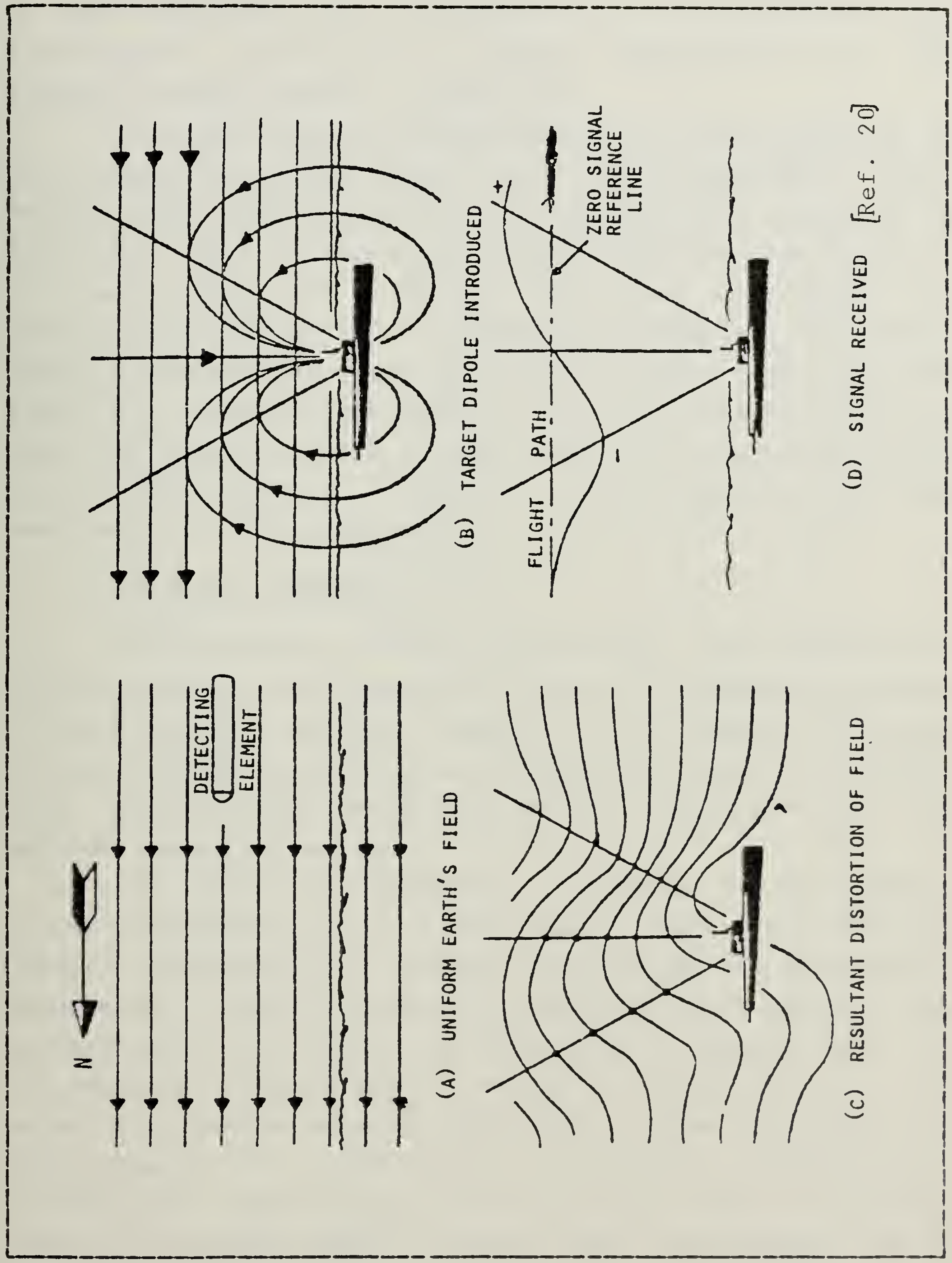
C. MAD SIGNAL AND BANDPASS

1. Source of the Signal

The MAD signal results from moving a magnetometer through the magnetic field of a submarine, which can be approximated by the field of a magnetic dipole. Figure 2.4 depicts the formation of a submarine caused anomaly.

The magnetic moment of an object in the earth's magnetic field can be due to permanent magnetization, magnetization induced by the earth's magnetic field, or a combination of both. In the case of a submarine hull both causes are present with a small amount of permanent magnetization produced by hull stress in metal components during construction and stress caused by submarine diving and surfacing. This, however, is a minor contribution. The most important constituent of the submarine magnetic moment is due to magnetization induced in the hull by the presence of the geomagnetic field. [Ref. 21]

The induced field of a submarine depends on the effective permeability along the vertical, athwartships, and longitudinal axes of the submarine. This information , taken together with the strength and dip angle of the geomagnetic field, yields a fairly precise calculation of the magnetic anomaly produced by the submarine. 'Deperming'


N
DETECTING ELEMENT
(A) UNIFORM EARTH'S FIELD
(B) TARGET DIPOLE INTRODUCED
(c) RESULTANT DISTORTION OF FIELD
FLIGHT PATH
ZERO SIGNAL REFERENCE LINE
+
-
(D) SIGNAL RECEIVED

[Ref. 20]

Figure 2.4 Formation of Submarine Caused Magnetic Anomaly (Simplified View Near Equator)

of the submarine hull cancels out the permanent hull magnetization leaving the induced magnetization as the principal signal source. [Ref. 21]

The MAD signal is approximated as the projection of the submarine dipole field onto the geomagnetic field vector. This approximation is good because the magnitude of the dipole field is very much smaller than the magnitude of the geomagnetic field (a few nanoTeslas as opposed to approximately 50000 nT). Therefore, whenever the dipole field is perpendicular to the earth's field a region of zero signal will result. The signal recorded by the AN/ASQ-81 or other MAD equipment is a mapping along the aircraft's flight path of this signal. Figure 2.5 qualitatively describes some aspects of the MAD signal.

2. Anderson Functions

The submarine anomaly signal shape is a function of the dip angle of the geomagnetic field, the magnetic heading of the aircraft, magnetic heading of the submarine dipole, and the lateral range between the aircraft and the submarine. These factors detwermine the 'A' coefficients for the Anderson functions below.

In 1949, J. E. Anderson of the Naval Air Development Center determined that the MAD signal, obtained along any course, consisted of a linear combination of three basic components. Different shaped signals could by changing the proportionsl contribution of these basic components. The mathematical representation of these components are now referred to as the Anderson functions. Using the dimensionless parameter 'b' (defined as the distance traveled along the aircraft track divided by the slant range at closest point of approach (CPA), b=0 at CPA) the anomaly can be represented by

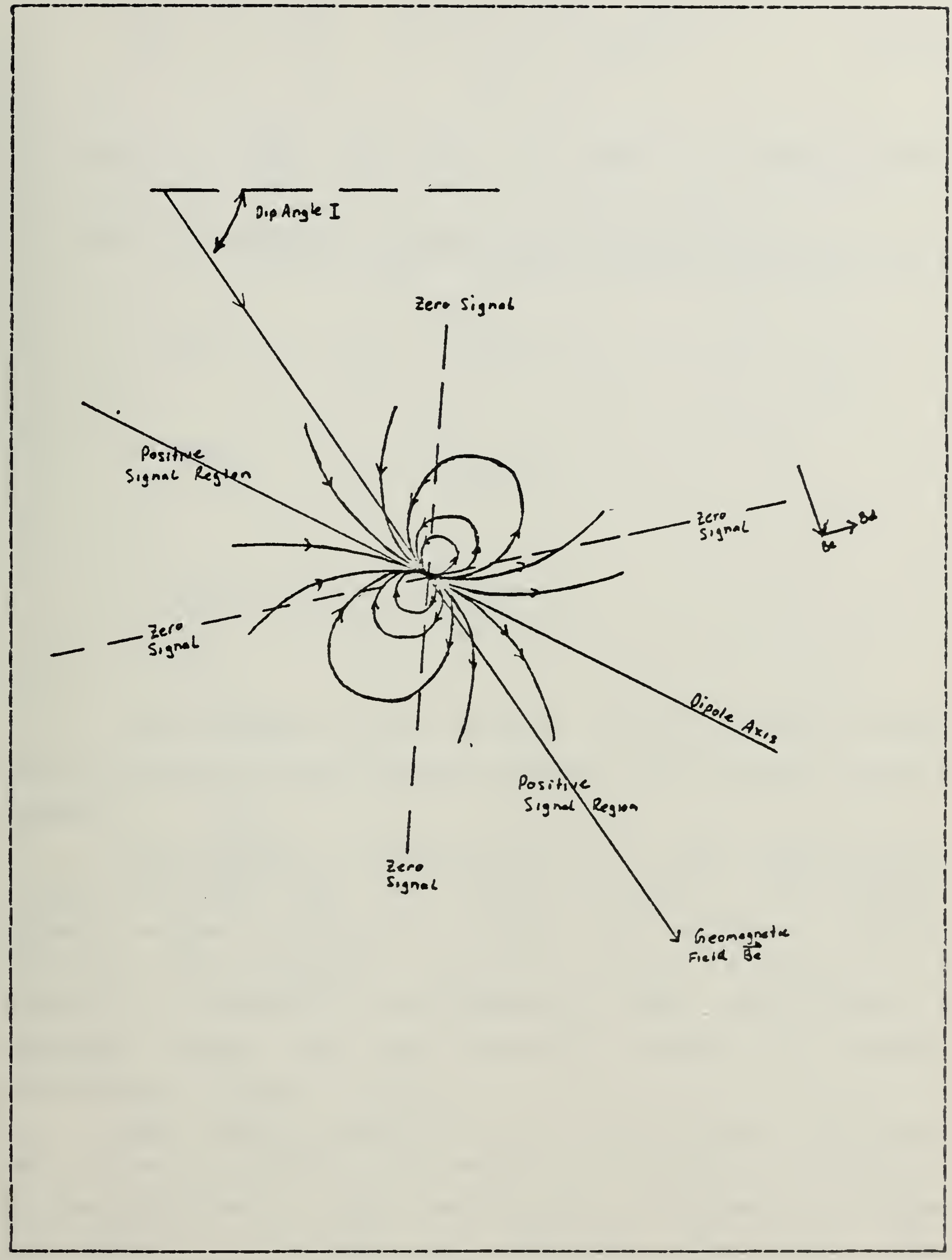


Figure 2.5 Qualitative Aspects of MAD Signal

$$Bs = \frac{M}{Z^3} \frac{A2\ b^2 + A1\ b + A0}{(b^2 + 1)^{5/2}} \qquad (2\text{-}1a)$$

$$\text{or } Bs = \frac{M}{Z^3} [A0\ f0(b) + A1\ f1(b) + A2\ f2(b)] \qquad (2\text{-}1b)$$

where M = magnetic moment of target dipole
Z = lateral range between target and plane at CPA

$$f0(b) = \frac{1}{(b^2 + 1)^{5/2}}$$

$$f1(b) = \frac{b}{(b^2 + 1)^{5/2}}$$

$$f2(b) = \frac{b^2}{(b^2 + 1)^{5/2}}$$

The strength of the detected signal is seen to fall off as the cube of the distance between the aircraft and the target.

By analyzing the functions and their coefficients, it can be shown that the optimum orientation for maximum anomaly signal detection is when the aircraft, target dipole, and geomagnetic field are lined up together as closely as possible. Specifically, this occurs when the submarine moment and the aircraft's track are oriented North-South. [Ref. 14, 21]

The Fourier transform of the component functions were taken to determine the frequency distribution of energy in the MAD signal. The anomaly signal components are shown in Figures 2.6 through 2.8 (Anderson) [Ref. 14]. The Fourier transforms of the signal components with a platform velocity of 150 knots are shown in Figure 2.9.

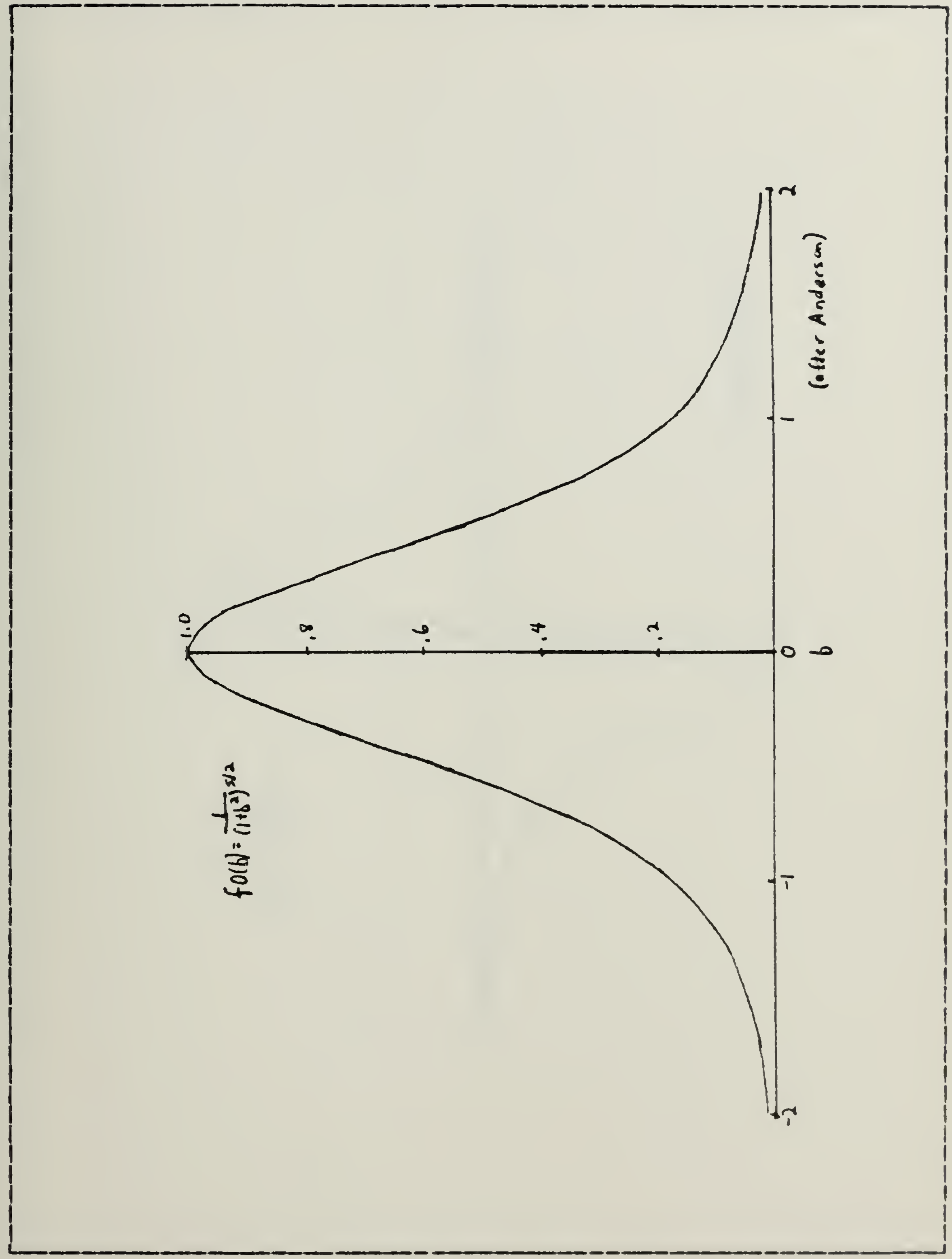


Figure 2.6 Basic MAD Component f0(b)

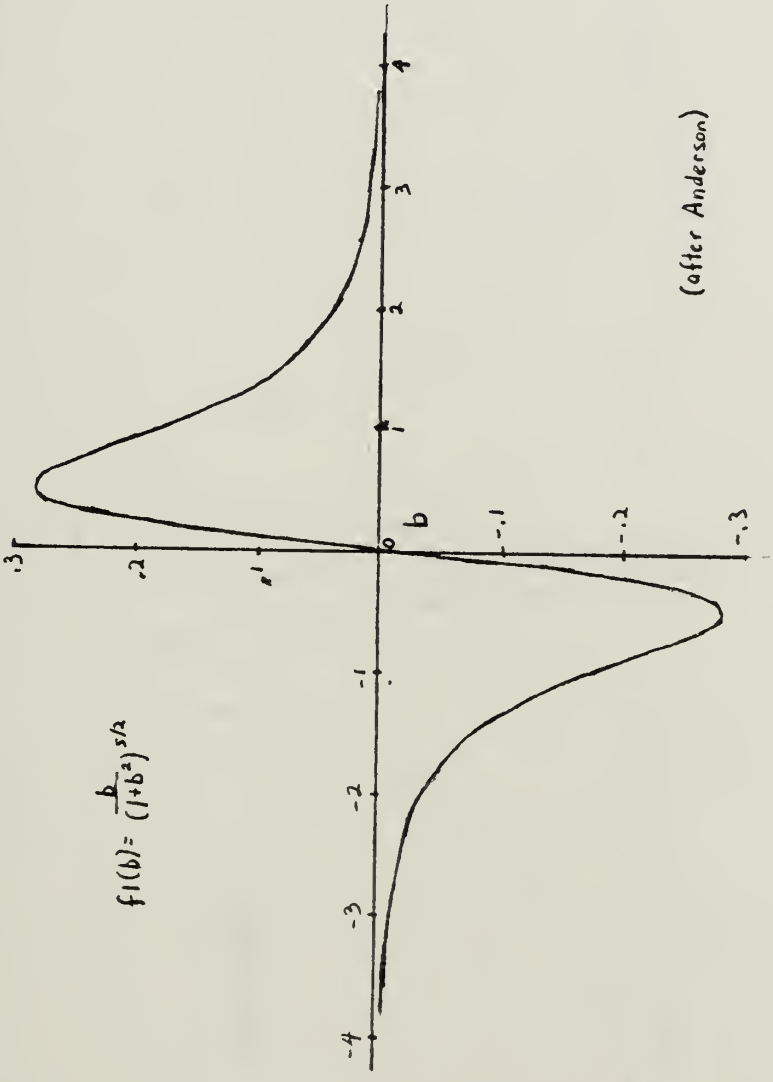


Figure 2.7 Basic MAD Component f1(b)

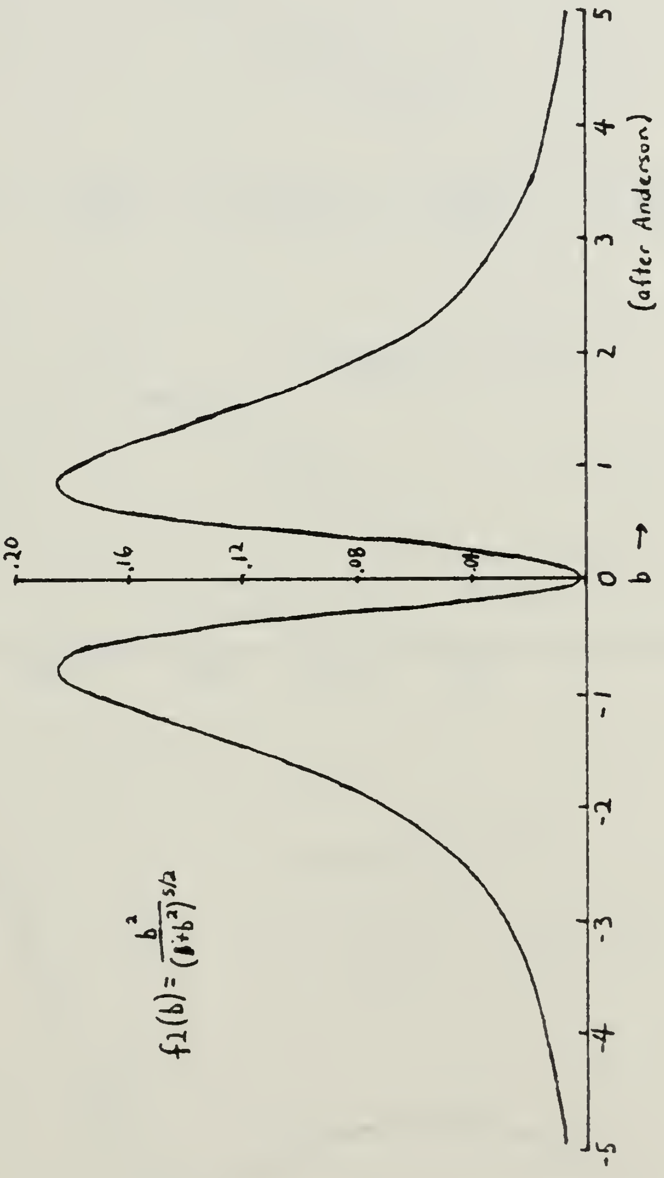


Figure 2.8 Basic MAD Component f2(b)

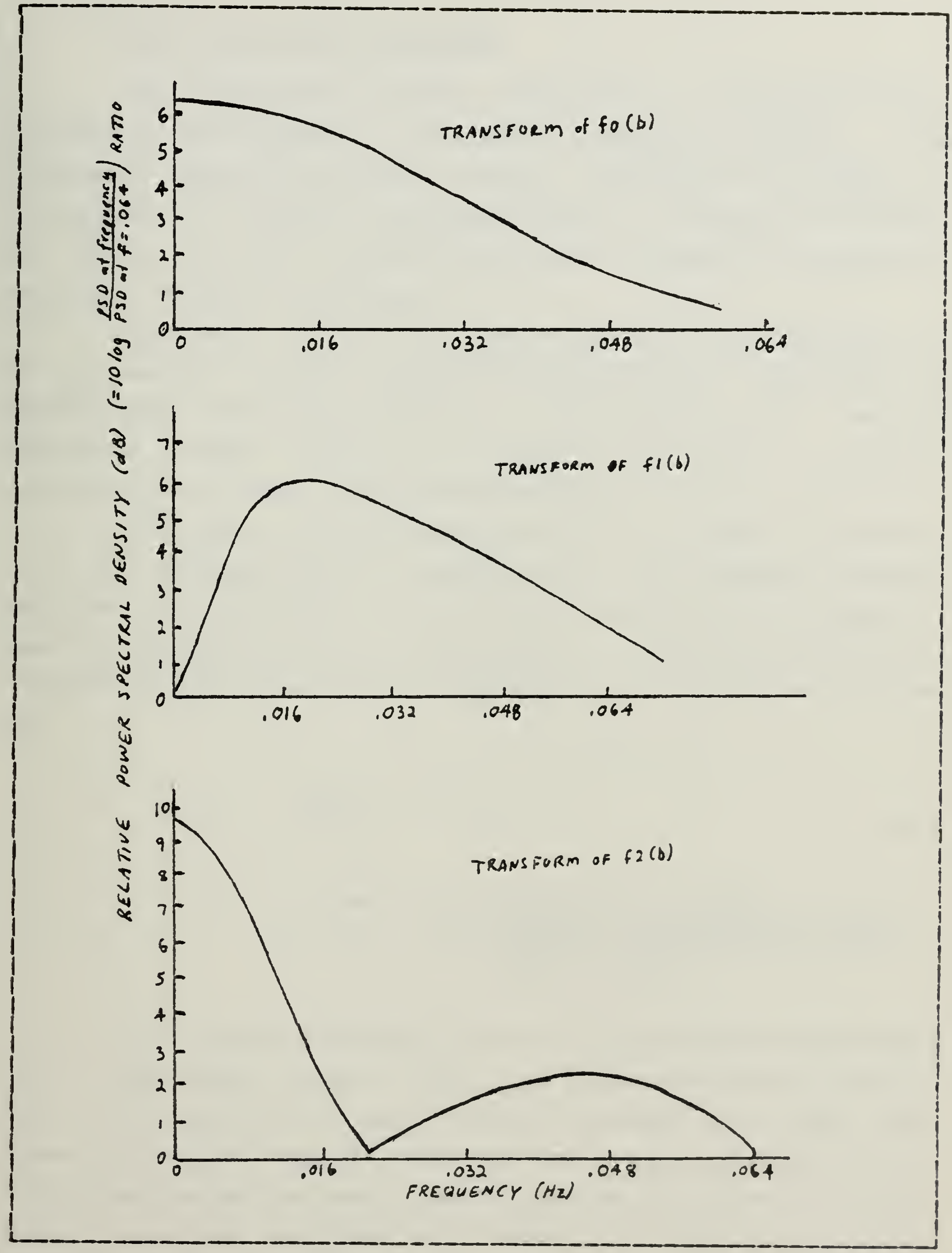


Figure 2.9 Frequency Spectrum (Fourier Transform) of MAD Signal Components

3. The MAD Filter Bandpass

The MAD signal, being a transient, is essentially a broadband (as opposed to a discrete frequency) signal. The frequency spectra of energy content shows how the signal is contained in a certain frequency range. In order to screen out unwanted noise, bandpass filtering is used in processing magnetic anomaly detections.

The major factors influencing the determination of an optimum MAD filter frequency are aircraft speed and the slant range from the aircraft to the target at CPA. Factors exerting a minor influence include dip angle, aircraft heading, and target dipole orientation.

The range in frequency variation is about an octave, with the higher values occuring when the passes are made parallel to the axis of the dipole and the lower when the pass is perpendicular to the dipole. Anderson empirically determined that the center frequency of the filter is given by

$$f = \frac{0.4\,v}{Z} \qquad (2\text{-}2)$$

where f = frequency in Hertz
v = aircraft velocity in ft/sec
and Z = greatest anticipated CPA range in feet

The ASQ-81 Bandpass Filter has highpass settings of 0.04, 0.06, 0.08, and 0.1 Hz, and lowpass settings of 0.2, 0.4, 0.6, and 2.0 Hz (Orion Service Digest 26) [Ref. 22]. There are no recommended settings for normal operation since background noise varies. The filter characteristics for the 0.06 to 0.6 Hz settings are shown in Figure 2.10 (Orion Service Digest 28) [Ref. 23].

The figure is a representation of the adjustable band pass filter of the ASQ-81 by itself. Other parts of the ASQ-81 system add in an additional high pass filter which adds another 12 dB/octave roll off to the low frequency end in Figure 2.10. Thus Figure 2.10 would represent the characteristics of the entire ASQ-81 system if the roll off of 36 dB/octave is changed to 48 dB/octave. [Ref. 24]

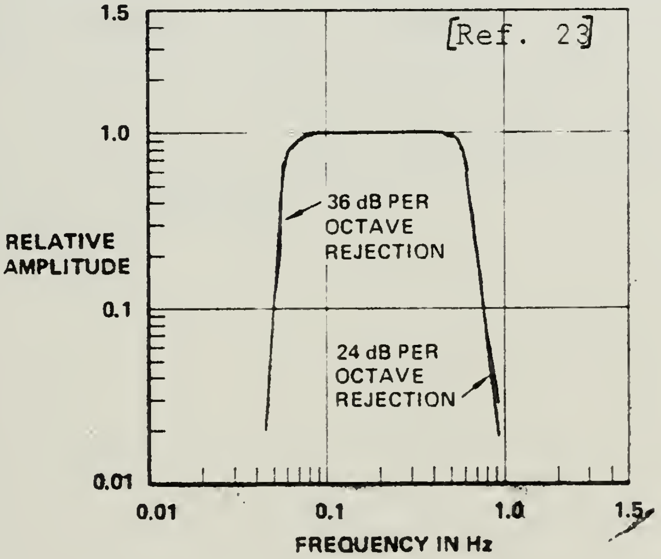


Figure 2.10 ASQ-81 Filter Characteristics: 0.06 - 0.6 Hz

Using equation 2-2, the center frequency for a MAD signal with a CPA slant range of 300 feet and aircraft velocity of 220 knots is 0.49 Hz. Using a lowpass filter setting above 0.6 Hz would not be very useful.

One reason the ASQ-81 filter extends up to 2.0 Hz instead of just 0.6 Hz is the following. The early Service Test Engineering Model (STEM) ASQ-81 that preceded the

current ASQ-81 production model had two bandpass filters, one adjustable from .04 to .6 Hz, and the other fixed at .75 to 10 Hz. During tests, the .75 to 10 Hz channel proved to be helpful in monitoring the STEM ASQ-81 "system" noise level. During design reviews for the production ASQ-81, it was decided that it might be useful to retain the ability to monitor "system" noise. In order to do this easily, the .75 to 10 Hz band was dropped and a 2 Hz position was added to the adjustable filter. [Ref. 24]

The center frequency at 1200 feet and 160 knots is .09 Hz. Consequently, the highpass filter settings could affect slower, longer range MAD detections.

The choice of the highpass (lower end of bandpass) settings have to be made after considering the noise present at time of system operation.

III. SOURCES OF MAD NOISE

A. INTRODUCTION

On a practical level MAD noise is defined as magnetic disturbances falling within the MAD passband (0.04 to 2.0 Hz, or since 0.6 Hz is the normal upper limit, 0.04 to 0.6 Hz) and having an amplitude greater than 0.01 nanoTeslas (the system sensitivity of the AN/ASQ-81 MAD system).

MAD noise sources can be divided into the following categories:

- Equipment Noise
- Aircraft Platform Noise
- Aircraft Manuever Noise
- Gradient Noise Due to Aircraft Motion Through the Geomagnetic Field
- Geologic Noise
- Noise from Wind Waves and Swells
- Geomagnetic Noise

B. SENSOR, PLATFORM AND MANUEVER NOISE

Sensor noise is the self-noise generated by the operation of the equipment itself. This can be partially due to the fact that the detector element is misaligned with respect to the geomagnetic field vector. Changes in lamp intensity, photodetector noise and noise in the electronic circuits can also contribute to sensor noise [Ref. 21]. The self-noise limitation of the ASQ-81 is 0.01 nT.

Platform noise is generated by components fixed to the aircraft in the vicinity of the sensor [Ref. 23]. Permanent, induced and eddy-current magnetic fields are

associated with the airframe. Permanent magnetic fields are due to aircraft structure or equipment having ferromagnetic parts. This field changes its orientation with respect to the geomagnetic field vector as the aircraft manuevers, causing field fluctuations near the magnetometer.

Platform noise is also induced in aircraft ferromagnetic structures by the geomagnetic field. Similarly, eddy-currents are induced in aircraft skin, ribs, and frames, and these currents , in turn, cause additional magnetic fields. Thus, rapid aircraft manuevers will induce changes in the magnetic field sensed by the magnetometer.

Platform noise in aircraft mounted sensors is countered by applying equal and opposite magnetic fields to the sensor in a process called compensation. Towed MAD systems are essentially free from this type of noise.

C. GRADIENT NOISE

Gradient noise can be divided into turn noise and noise due to changes in altitude.

Turn noise is a problem when 'MAD trapping' or using MAD for tracking a target. The earth's magnetic field has a horizontal gradient (in this case the magnitude varying with latitude). As the aircraft moves in the direction of the gradient the field strength changes. The noise due to a MAD trapping or hunting circle is centered in frequency at the reciprocal of the time taken to complete one revolution. In the case of a two-minute circle, the noise would be centered at 0.00833 Hz, well below the filter used in the ASQ-81. The horizontal gradient noise due to flying a cloverleaf pattern, for the most part, also falls below the MAD passband. [Ref. 21]

Vertical gradient noise is due to changes in sensor altitude. An altitude gradient of up to 0.005 to 0.01 nT

per foot exists in the earth's main field. In areas of geological anomalies this gradient is even larger. Fast altitude or aircraft pitch changes can cause a magnetic field fluctuation of sufficient amplitude to be of concern. To avoid vertical gradient noise, altitude compensation equipment is used. [Ref. 23]

D. ENVIRONMENTAL NOISE

Magnetic noise from sources existing in the natural environment include geologic noise, temporal variation in the earth's magnetic field, and noise due to ocean waves and swells.

Geologic noise has its source in naturally occuring magnetic anomalies caused by magnetic material present in the earth's crust. When the sensor passes over geological anomalies, the relative motion causes a MAD-like signal to be recorded. Geologic noise is usually more pronounced in shallow water as the sensor is much closer to the source of the noise. Geological magnetic anomalies are often associated with such oceanographic features as seamounts and ocean ridges.

Sea water is a conducting medium which is transported by the physical motion of water waves in the presence of the geomagnetic field. This motion induces currents in the sea. These currents give rise to secondary magnetic fields, which add vectorially to the quasistatic, geomagnetic field (Weaver) [Ref. 25]. These fields can be detected at significant distances above the sea surface and fall off exponentially with altitude. Figure 3.1 is a plot for several surface wave periods of the induced magnetic field per meter amplitude of the surface wave. These induced fields can be a problem at the low altitudes where MAD is used.

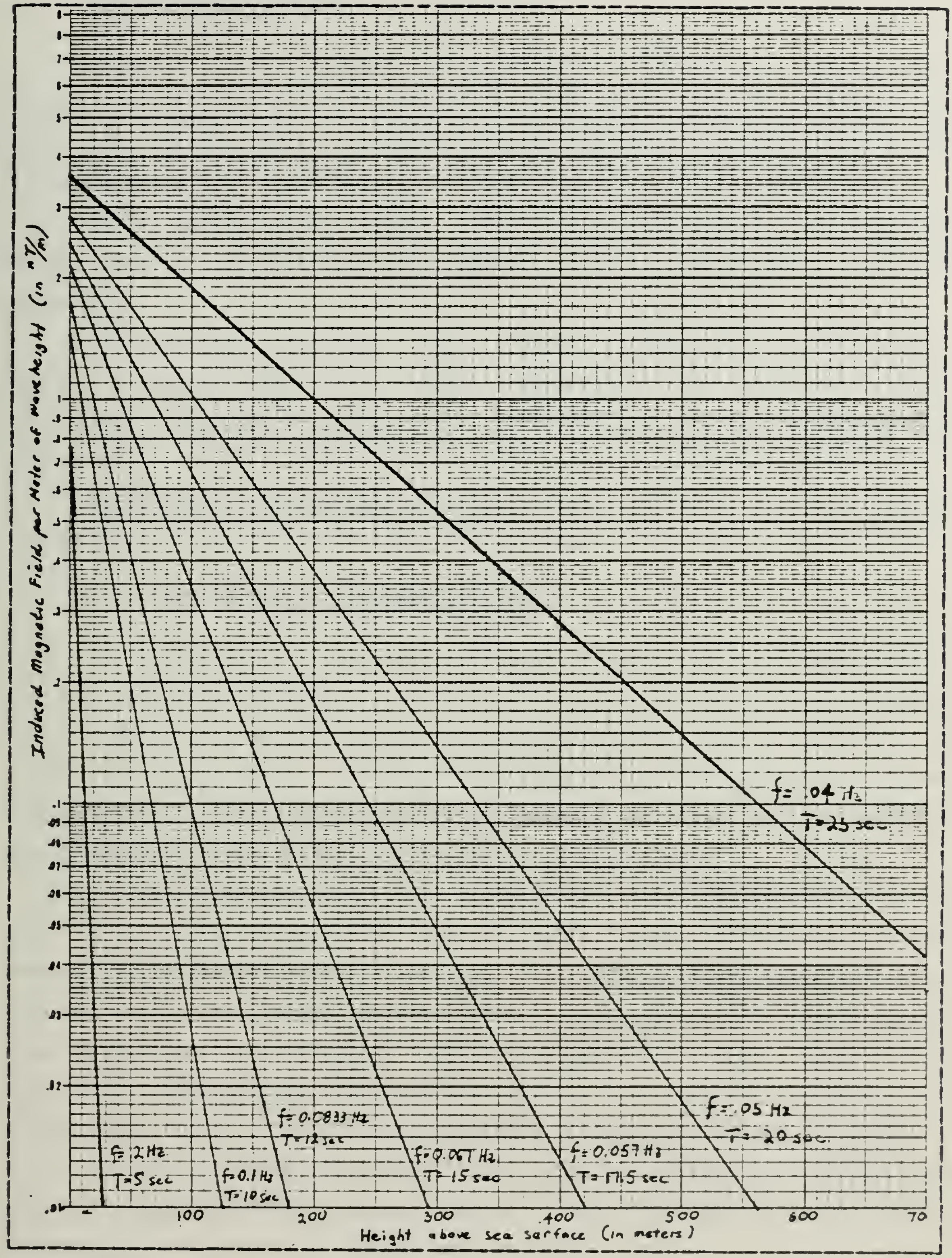


Figure 3.1 Induced Magnetic Field per Meter of Waveheight

E. GEOMAGNETIC NOISE

Temporal variations in the earth's magnetic field with frequencies in the MAD bandpass and amplitudes greater than 0.01 nT have become known as _geomagnetic noise_ in the MAD literature.

Quiet daily variations, such as the Sq and L variations, have periods sufficiently long to fall far below the MAD passband.

Geomagnetic storms have been discussed previously. Rapid fluctuations with high amplitude and falling within the MAD passband occur in connection with geomagnetic storms.

Geomagnetic micropulsations comprise the last category of geomagnetic noise to be discussed.

1. _Geomagnetic Micropulsations_

Geomagnetic micropulsations are rapid fluctuations of the earth's magnetic field with periods from 0.2 seconds to 10 minutes and amplitudes from about 0.1 nT to as high as a few tens of nT's. These fluctuations are caused by electromagnetic perturbations propagating in the magnetosphere as hydromagnetic waves (Nishida). [Ref. 26]

Micropulsations are classified by morphology, that is, by examining periods, amplitudes, times of occurence and other observed characteristics. Micropulsations have been placed into two broad categories: _irregular_ and _continuous_. The irregular pulsations are represented by the symbol Pi, and the continuous pulsations by Pc. Table II shows the breakdown by period of the various micropulsation classes.

It can be seen that for MAD geomagnetic noise the lower frequency Pc1, Pc2, Pc3, and Pi1 pulsations are of interest.

TABLE II

Geomagnetic Micropulsation Classes

NOTATION	PERIOD (sec)	AVERAGE AMPLITUDE (nT)
Pc1	0.2 - 5.0	0.05 - 0.1
Pc2	5 - 10	0.1 - 1.0
Pc3	10 - 45	0.1 - 1.0
Pc4	45 - 150	0.1 - 1.0
Pc5	150 - 600	1 - 10
Pi1	1 - 40	0.05 - 0.1
Pi2	40 - 150	1 - 5

(after Jacobs)

Pc1 pulsations are regular sinusoidal oscillations with periods normallly falling in the 0.3 to 4 second (0.25 to 3.33 Hz frequency) range. Pc1's may start as separate bursts and gradually develop into a series of pulsations which could last for hours. They may also occur as consecutive groups of pulsations with sharply varying frequencies. The average amplitude of Pc1's is 0.05 to 0.1 nT and they tend to have a single well defined frequency. Pc1 pulsations with frequency less than 0.5 Hz are more common at high latitudes than at mid latitudes. These pulsations occur in the daytime in the auroral zone, and at night and early morning hours in lower latitudes. Pc1's are characteristic of the quiet and weakly disturbed states of the geomagnetic field and show an increase in activity one to two hours before, and four to seven days after, a magnetic storm. [Ref. 6]

Pc2 and Pc3 pulsations are grouped together in most characteristics. The amplitudes of the oscillations are usually under 0.5 nT and the typical frequency range is 0.03 to 0.2 Hz. These pulsations are normally found during the day with their activity reaching a maximum around noon. Pc3 pulsations show a seasonal variation with a minimum of activity occuring during winter.

Pc4 and Pc5 are large amplitude fluctuations, but fall below the frequency band of interest for MAD.

Pi1 pulsations have an irregular form with an average amplitude of 0.01 to 0.1 nT and a frequency mainly in the 0.10 to 0.17 Hz range. Spectral analysis of these pulsations show a braod band of frequencies. Pi1 amplitudes have maximum values in the auroral zones, with the intensity of the pulsations decreasing with decreasing latitude. Pi1's are normally observed in the late night and early morning hours, and show an increase in activity with increased geomagnetic field disturbance. [Ref. 6]

Geomagnetic micropulsations can be observed anywhere on the globe, at various times of day and year, and in both quiet and disturbed geomagnetic field conditions.

IV. METHODS OF EVALUATING GEOMAGNETIC ACTIVITY

A. INTRODUCTION

Previous chapters have defined geomagnetic activity as it applies to Magnetic Anomaly Detection. In this chapter, methods of evaluating that activity will be examined, including methods currently in use by the fleet.

B. GEOMAGNETIC INDICES

A geomagnetic index is simply a measure used to quantify and describe time variations of the earth's magnetic field resulting from solar-terrestrial relationships. These indices are commonly used to express the intensity and depict the character of geomagnetic activity throughout the day.

For the most part, geomagnetic indices developed as range indices, measuring the difference between the high and low values for different field components measured during the day by magnetic observatories (Lincoln) [Ref. 27]. Most current indices are of the range type, but other indices have been developed which are more subjective or qualitative in nature.

Geomagnetic indices are designated by a letter code such as: C, Ci, Cp, C9, Q, R, W measure, Dst, K, Ks, Kp, ak, Ak, ap, and Ap. There are additonal indices in use.

The C, Ci, Cp, and C9 indices are daily magnetic field character figures. The C index is the daily character figure for a single observatory. In this scale, C=0 indicates a quiet day, C=1 a moderately disturbed day, and C=2 a heavily disturbed day. The daily international character

figure, Ci, is the arithmetic mean of the C indices reported by participating observatories around the world. Cp, the daily planetary character figure, is similar to Ci, except that it is derived from the values of Kp and ap. C9 is a contracted scale for Ci an Cp with single digit values running from 0 to 9 (Bartels). [Ref. 28].

The Q and R indices are quarter-hourly and hourly range indices respectively, taken at high latitude stations only.

The W measure is an index of the equatorial electrojet. Dst is a measure of ring current effect. They are both amplitude indices. [Ref. 27]

1. K, a, and A Indices

The K, Ks, Kp, ak, Ak, ap, and Ap indices comprise a group of related 3-hour range indices. The K index is a single station code using a quasi-logarithmic scale from 0 to 9 to measure geomagnetic activity. The value of K is determined by first determining the difference between the lowest and highest deviations from the regular daily variation (Sq) during a 3-hour period. This range (in nT) is converted to the K scale based on the historical activity ranges at the particular observatory involved [Ref. 27]. The conversion for the Fredericksburg, Virginia observatory is given in Table III. This conversion can also be applied to the USAF/NOAA observatory in Boulder, Colorado [Ref. 29].

The Ks index is a standardized K index which is freed from local variations and is then used to determine the planetary 3-hour index, Kp.

The equivalent three-hour-range, ak, is a conversion of the K index as shown in Table IV. In order to detemine the units of ak for a particular observatory, divide the lower range limit of K=9 by 250. Thus for Fredericksburg and Boulder, ak is in 2-nT units.

TABLE III

Conversion from Range to K for Fredericksburg, Va.

K	Range(nT)
0	0 - 5
1	5 - 10
2	10 - 20
3	20 - 40
4	40 - 70
5	70 - 120
6	120 - 200
7	200 - 330
8	330 - 500
9	>500

(after Lincoln)

TABLE IV

Equivalent Range ak for Given K

K	0	1	2	3	4	5	6	7	8	9
ak	0	3	7	15	27	48	80	140	240	400

(after Lincoln)

Ak is the equivalent daily amplitude and is the average of the eight daily ak values at a particular observatory. This index is promulgated using the name of the observatory, the Ak index for Fredericksburg is known as the A-Fredericksburg or A-Fred index.

The equivalent planetary amplitude, ap, is determined from the Kp index in a fashion similar to that of determining ak from the K indices. The eight ap values for a given day can then be averaged into the daily equivalent planetary amplitude Ap. These two indices are given in 2-nT units.

C. GEOMAGNETIC INDICES IN FLEET USE

1. Current Usage

Geomagnetic indices of interest in connection with MAD operations are the K, Ak, and Ap indices.

Fleet operators utilize the "alpha Index' for perdicting geomagnetic activity over the entire world [Ref. 30]. This index is promulagated by the Fleet Numerical Ocenaographic Center, Monterey, California, in the environmental briefings received by aircrew personnel. This index is the Ap index as sent out from the Space Environmental Services Center, Boulder, Colorado in the Joint USAF/NOAA Report of Solar and Geophysical Activity [Ref. 31].

The Boulder K index is available to interested parties by telephone recording and in the WWV and WWVH radio broadcasts and is therefore available to fleet users [Ref. 32].

The Ak index for the Fredericksburg, Virginia observatory has been used in studies of gecmagnetic activity as applied to Magnetic Anomaly Detection [Ref. 33].

2. Theoretical Applicability of A and K Indices to MAD

With the widest useful filter settings, the MAD bandpass ranges from 0.04 to 0.6 Hz (1.7 to 25 seconds in period). As such, in order for a geomagnetic index to be directly applicable for MAD use, it should be sensitive to that frequency range.

The K indices, and the K-derived A indices, are not especially sensitive to the MAD range. Mayaud [Ref. 34] indicates that these indices are mainly sensitive to fluctuations whose periods are much longer than the lower end of the frequency range analyzed, that is, a frequency corresponding to a period of 45 minutes (0.0004 Hz).

One reason for this lack of sensitivity for MAD bandpass geomagnetic noise is that the amplitude of geomagnetic fluctuations varies inversely with frequency, so that the amplitude of the fluctuation increases as the as the frequency decreases. It can therefore be seen that the fluctuations with periods of an hour or greater largely determine the variation range used to calculate the K index. The activity driving the K and A indices, will, because of band pass filtering, not even be observed by the MAD system, and the activity of interest to MAD might not influence the K or A indices at all. It can be concluded that there is no direct physical link between MAD geomagnetic noise and either the K or A indices. [Ref. 35]

3. Experimental Correlation of A and K Indices with MAD Band Noise

a. ASQ-10A Study

Brennan and Smits [Ref. 33] found that geomagnetic micropulsation activity was recorded at their ASQ-10A MAD magnetometer site in Maryland, when the A-Fredericksburg index was greater than 25. This occured everytime they were recording data with A-Fred greater than 25. It is important to note that they observed additional activity during some periods when A-Fred was less than 25.

The Brennan and Smits study tends to validate the use of the A indices as at least qualitative indications of geomagnetic noise in the MAD bandpass. Their study, however, was specific to the ASQ-10A magnetometer system which has a sensitivity of 0.1 nT as opposed to the 0.01 nT sensitivity of the ASQ-81 system. The effect of the ASQ-10 sensitivity is to filter out most Pc1 pulsations. As Pc1 pulsations do not correlate well with the A and K indices, the filtering out of these pulsations would tend to increase

the reliability of the A-Fred or Ap indices as measures of MAD geomagnetic noise. Mason [Ref. 36] stated that the "occurence of Pc1 is well known to be associated with low Kp values." It should be noted that an operational drawback of the filtering out of Pc1 pulsations by the ASQ-10A is that the system also filters out valid signals of less than 0.1 nT amplitude.

While information has been presented that suggests the the A-Fred index can be useful for MAD geomagnetic noise evaluation for the AN/ASQ-10A system, sufficient data was not presented to draw conclusions for index usage with the AN/ASQ-81 system.

b. ASQ-81 Study

For two weeks in April 1976, Naval Air Development Center personnel operated a geomagnetic observatory at the Atlantic Undersea Test and Evaluation Center in the Bahamas. The primary magnetometer used for this observatory was the ASQ-81 magnetometer. One purpose of this observatory was to compare the K index (as determined by the San Juan Observatory) with geomagnetic activity in the MAD band pass. The conclusion of this study was that the K-San Juan index did not correlate with geomagnetic noise in the MAD band pass. [Ref. 37]

We have undertaken a correlation analysis using the Fisher Z transformation [Ref. 38] of the NADC data furnished to us by Ochadlick. The data used is listed in Tables V and VI.

TABLE V

Observed AUTEC Data and Indices, April 11-18, 1976.

Date	Time (Z)	K-San Juan	Ap	Maximum Amplitude (nT)
11	0300	1	12	0.17
11	0600	2	12	0.14
11	1500	2	12	0.62
12	0000	2	9	0.21
12	0300	3	9	0.28
12	0600	3	9	0.28
12	1500	0	9	0.23
12	1800	1	9	0.44
13	0000	2	13	0.39
13	0300	2	13	0.80
13	0600	0	13	0.80
13	0900	1	13	0.24
13	1200	1	13	0.30
13	1500	0	13	0.31
13	1800	2	13	0.30
13	2100	3	13	0.51
14	0000	2	15	0.07
14	0300	2	15	0.13
14	0600	2	15	0.24
14	0900	2	15	0.26
14	2100	3	15	0.26
15	0000	0	4	0.16
15	0300	0	4	0.07
15	0600	0	4	0.05
15	0900	1	4	0.09
15	1200	0	4	0.24
15	1500	0	4	0.15
15	1800	1	4	0.19
15	2100	1	4	0.30
16	0000	1	8	0.11
16	0300	3	8	0.48
16	0600	3	8	0.09
16	0900	2	8	0.12
16	1200	0	8	0.19
16	1500	0	8	0.24
16	1800	1	8	0.12
16	2100	2	8	0.30
17	0000	1	5	0.11
17	0300	3	5	0.14
17	0600	1	5	0.10
17	0900	0	5	0.04
17	1200	0	5	0.08
17	1500	1	5	0.10
17	1800	1	5	0.07
18	0000	0	2	0.07
18	0900	0	2	0.18
18	1200	0	2	0.10
18	1500	0	2	0.10
18	2100	0	2	0.07

(after Ochadlick)

TABLE VI

Observed AUTEC Data and Indices, April 19-24, 1976.

Date	Time (Z)	K-San Juan	Ap	Maximum Amplitude (nT)
19	0000	1	5	0.26
19	0300	1	5	0.16
19	0600	1	5	0.05
19	0900	1	5	0.07
19	1200	0	5	0.05
19	1500	0	5	0.10
19	1800	1	5	0.11
20	0300	1	2	0.05
20	0600	0	2	0.04
20	0900	0	2	0.08
20	1200	0	2	0.08
20	1500	0	2	0.06
20	1800	1	2	0.07
20	2100	0	2	0.07
21	0000	0	5	0.12
21	0300	0	5	0.04
21	0600	1	5	0.11
21	0900	0	5	0.14
21	1200	0	5	0.06
21	1800	1	5	0.11
22	0000	3	19	0.10
22	0600	4	19	0.32
22	0900	3	19	0.21
22	1200	1	19	0.36
22	2100	2	19	0.45
23	0000	2	8	0.12
23	0300	2	8	0.17
23	0600	1	8	0.05
23	0900	0	8	0.15
23	1200	1	8	0.08
23	1500	1	8	0.17
23	1800	1	8	0.09
23	2100	2	8	0.17
24	0300	2	16	0.38
24	0600	3	16	0.21
24	0900	2	16	0.08
24	1200	1	16	0.14

(after Ochadlick)

The largest peak-to-peak fluctuations observed on the ASQ-81 magnetometer in a three hour period was compared to the K-San Juan index for that period. Data points with fluctuations greater than 1.0 nT were deleted as the observatory did not record that information. The sample coefficient of linear correlation was 0.34 with the .95 confidence interval for the actual correlation coefficient

being from 0.14 to to 0.52. Sample size was 86. This indicates that there is at most a weak correlation between the observed data and the K-San Juan index. A much greater correlation would be required for the K index to be of any significant value for MAD operational use.

The coefficient of correlation has values from -1.0 to 1.0. A value of -1.0 or 1.0 indicates perfect negative or positive correlation, respectively. A value of zero signifies no correlation at all.

A similar correlation analysis against the Ap index was conducted. The sample correlation coefficient was 0.51 with the .95 confidence interval for the actual coefficient of correlation being from 0.32 to 0.65. Again, this signifies that only a weak correlation was observed.

The weak correlation between observed geomagnetic activity and the K-San Juan index suggests that this index would not be very useful in describing MAD geomagnetic noise, as this K index reflected activity similar to that in the band of interest only about one-third of the time. The stonger correlation of the Ap index indicates that it reflected activity similar to MAD geomagnetic noise about one-half of the time. This is still not a very good indication of what is going on in the MAD band pass.

c. Power Spectral Density Evaluation

As part of ongoing research at the Naval Postgraduate School, geomagnetic activity data in the range of the MAD band pass has been collected and analyzed in the form of power spectral density (PSD) curves.

A measure of MAD band activity has been developed by integrating under the PSD curve and using compromise band pass limits of 0.05 and 1.0 Hz. This type of index is discussed in depth later.

Two sets of data were analyzed. One set was taken using an induction coil to measure the fluctuations in one direction during May, 1980 [Ref. 39] and August to October, 1981 [Ref. 40]. The other data set was collected using a Cesium vapor toatal field magnetometer during the July to October, 1980 period [Ref. 41].

Correlation analysis of the single-coil system data yielded a sample correlation coefficient of 0.401 for the K-Fredericksburg index, 0.180 for the A-Fredericksburg index and 0.155 for the Ap index. Sample size was 9. The .95 confidence intervals for the correlation coefficient for K-Fred, A-Fred, and Ap were -.36 to .85, -.55 to .76, and -.56 to .75, respectively. The data for this test is presented in Table VII.

TABLE VII

Single Coil RMS Noise Data and Indices

Date	Time(Z)	RMS Noise Amplitude(nT)	K-Fred	A-Fred	Ap
1 May 80	1800	0.10	3	10	8
21 Aug 81	2045	0.05	2	12	14
25 Aug 81	0235	0.12	3	15	16
25 Aug 81	0745	0.19	3	15	16
25 Aug 81	1318	0.05	3	15	16
4 Oct 81	1830	0.06	3	17	17
5 Oct 81	0155	0.12	1	7	7
5 Oct 81	0630	0.09	3	7	7
5 Oct 81	1530	0.02	0	7	7

The Cesium vapor magnetometer data yielded sample coefficients of correlation of 0.552, 0.374, and 0.444 for the K-Fred, A-Fred, and Ap indices, respectively. The sample size was 14. The .95 confidence intervals were for K-Fred from .03 to .84, A-Fred from -.20 to .76, and for Ap from -.12 to .79. The Cs vapor magnetometer data is presented in Table VIII.

TABLE VIII

Cs Vapor RMS Noise Data and Indices, Jul-Oct,1980

Date	Time(Z)	RMS Noise Amplitude(nT)	K-Fred	A-Fred	Ap
25 Jul	1800-1830	0.10	6	31	46
30 Jul	1450-1520	0.06	2	7	8
30 Jul	1520-1551	0.07	2	7	8
31 Jul	1450-1520	0.05	1	6	6
31 Jul	1520-1555	0.04	1	6	6
16 Aug	0030-0100	0.05	2	19	26
16 Aug	0900-0930	0.04	2	19	26
18 Oct	0230-0300	0.06	3	17	21
18 Oct	0300-0330	0.06	4	17	21
18 Oct	0630-0700	0.04	4	17	21
18 Oct	1030-1100	0.04	3	17	21
18 Oct	1100-1130	0.05	3	17	21
18 Oct	1230-1300	0.04	3	17	21
18 Oct	1300-1330	0.04	3	17	21

Although the sample sizes used were too small to draw any meaningful conclusions, there is little evidence to suggest that any of the K-Fred, A-Fred, or Ap indices is a very accurate measure of geomagnetic noise in the ASQ-81 MAD band pass.

d. Correlation Conclusions

Although some weak correlation does exist between the K indices, the A-Fred index, the Ap index and geomagnetic noise in the MAD band pass, this correlation is incidental and indirect, being the result of a correlation between the activity in the MAD band and in the lower frequency activity that influences the K and A indices. These indices are not directly influenced by activity in the MAD band. The correlation that does exist does not appear to be sufficiently high to enable these indices to yield accurate indications of the actual MAD band activity. The use of these indices for anything except the roughest qualitative estimation of active in the MAD band pass is not recommended.

D. PROPOSED GEOMAGNETIC INDICES FOR MAD

Overall geomagnetic acitivity is analyzed in both the time and frequency domains. Geomagnetic noise indices for the MAD band pass could be developed in either of these domains.

The spatial coherence of MAD geomagnetic noise has not yet been adequately determined. This information would be necessary in order to determine the number and location of mini-observatories for an operational MAD noise index.

1. Time Series Analysis

One way to develop an index of MAD geomagnetic activity would be to establish mini-observatories near bases from which MAD operations are conducted. These observatories would use ASQ-81 magnetometers or different magnetometers with ASQ-81 filter networks, and could in real time record the geomagnetic noise in the MAD band. A measure such as the maximum peak-to-peak (or possibly the average peak-to-peak) noise in a given time period could then be disseminated to flight crews operating in the area covered by that index. Obviously, the spatial coherence of MAD band activity is important in making such a system work. This type of mini-observatory has been suggested by References 31 and 35.

2. Frequency Domain Index

Present fleet procedures examine MAD noise such as system and manuever noise in terms of the amplitude of the fluctuation [Ref. 30]. An index of geomagnetic noise in the MAD band pass would therefore be of greatest usefulness to the fleet operator if it were in units of the amplitude of the signal as seen by the MAD equipment.

The method proposed to derive a MAD noise index in the frequency domain begins with obtaining the power spectral density of the activity in the MAD band by Fourier analysis of the time series data input from the magnetometer.

By intergrating under the PSD curve over the limits of the MAD bandpass, a value in units of amplitude^2 will result. Taking the square root of this value will yield an RMS amplitude. Equation 4-1 represents the derivation of this index.

$$\text{MAD Index} = \left(\int_{l}^{u} PSD(f)\, df \right)^{1/2} \qquad (4-1)$$

where MAD Index is in nT (gammas)
f = frequency (Hz)
u = upper bandpass limit
l = lower bandpass limit
and PSD(f) = power spectral density (nT^2/hz)

The characteristics of the MAD filter (the filter not being an ideal bandpass filter) could be applied prior to the integration. The integration itself could be done by either a point-by-point numerical integration or by first modelling the PSD curve by polynomial curve fitting and then integrating the polynomial over the range of the band pass. It is anticipated that this could be done in close to real time by a digital computer, possibly by a desk top computer such as the HP9845.

The type of sensor utilized could be the ASQ-81 magnetometer, other total field magnetometer, or possibly an orthogonal 3-coil system whose signals can be combined to yield the projection on the total field vector of the fluctuations. A single coil system oriented in the direction of the earth's magnetic field vector could also be used.

A three coil system which is used to yield an RMS amplitude is currently in research use at the Naval Postgraduate School.

3. Predictions of Geomagnetic Activity

The proposed indices discussed above are intended to be real time measures of the geomagnetic noise in the MAD bandpass. Whether or not such activity can be predicted ahead of time needs to be looked into.

While there is no model for the background component of geomagnetic noise, work has been done on estimating the future activity of micropulsations, notably by Fraser-Smith in the case of Pc1 pulsations [Ref. 42, 43]. By extending the prediction technique for Pc1 pulsations to the Pc2, Pc3, and Pi1 pulsations, the occurrence of geomagnetic micropulsation activity in the MAD band might be predicted. Combining this prediction with real-time solar flare information should give the capability to disseminate real-time and estimated future MAD index values to fleet users.

Previous studies have led to the conclusion that the currently used geomagnetic indices are not accurate measures of geomagnetic noise in the MAD band pass. Experimental equipment has been utilized, and computer software written in order to confirm this conclusion, and to develop a replacement means of evaluating MAD geomagnetic noise.

A. EQUIPMENT CONFIGURATION

Experimental equipment, acquired as part of the Naval Postgraduate School geomagnetics research program, has been utilized in the effort to develop a usable MAD index. This equipment is in use in other projects of the geomagnetics research group. The sensors and associated equipment are set up for remote site operation with system monitoring and data analysis located at the Naval Postrgraduate School. Descriptions of the data collection system and data analysis system follow below.

1. Data Collection System

The data acquisition system illustrated in Figure 5.1 reveals the following major components:

- coil antenna sensors (3)
- preamplifiers (3)
- signal conditioners (amplifiers) (3)
- pulse code modulation system (1)
- radio transmitter (1)
- radio receiver (1)
- instrumentation tape recorder (1)

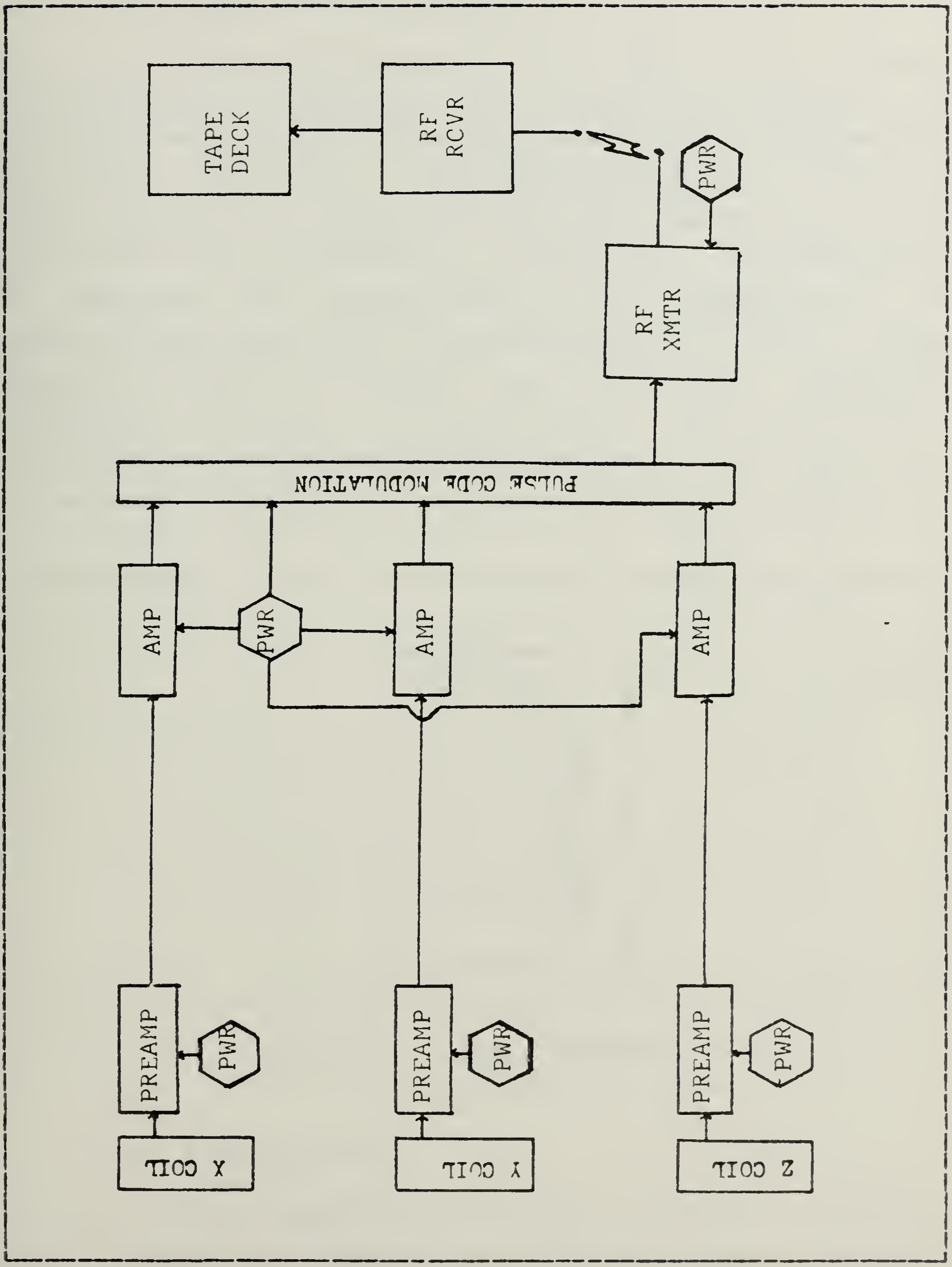


Figure 5.1 Data Collection System

a. Coil Antenna Sensors

Three coil sensors are used in this system. Each sensor is a self-supporting, continuously wound, non-center-tapped coil antenna manufactured by Elma Engineering, Palo Alto, California, from about 5460 turns of 18 gauge copper magnet wire. The coils weigh approximately 50 kg each with dimensions as depicted in Figure 5.2. The dimensions of the sensor are constrained by the dimensions of the largest glass sphere that is commercially available. These spheres are used to enclose the coils during underwater experiments. The coil resistance is 120 ohms and its self-inductance is approximately 9.31 henries. The three coils are mounted orthogonaly on a nonmagnetic frame (Figure 5.3).

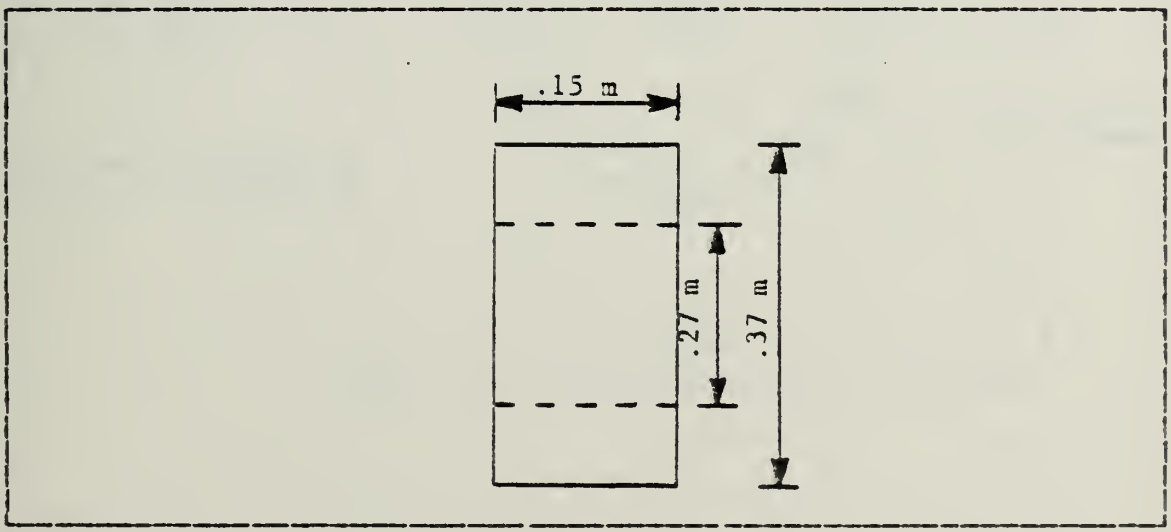


Figure 5.2 Sensor Dimensions

b. Preamplifier

The preamplifier used was the model 13-10A low noise ELF amplifier manufactured by Dr. Alan Phillips of SRI

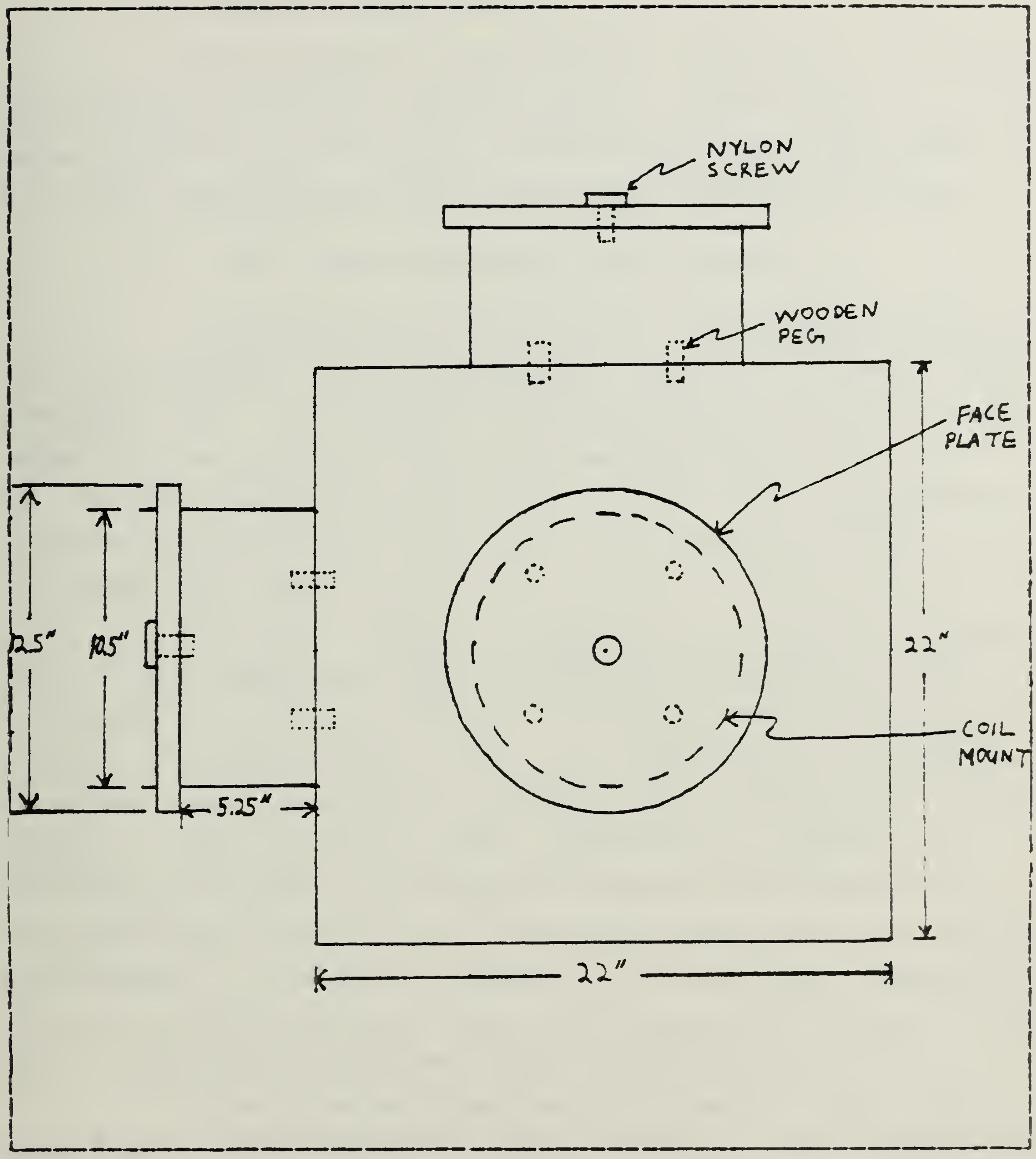


Figure 5.3 Sensor Mounting Block

International. The final stage of the amplifier contains an active low-pass filter which provides a sharp cutoff for frequencies above 20 Hz. The overall preamplifier gain for inputs of less than 2.5 millivolts is 60 dB.

c. Signal Conditioners

The signal conditioners receive the analog signals from the coil preamplifiers, amplify them on the order of 30 dB, and limits signals with peak amplitudes of 7.5 volts from entering the pulse code modulation system.

d. Pulse Code Modulation (PCM) System

The pulse code modulation system chosen for use is one designed and manufactured by Dr. Robert Lowe, Lowecom, Inc. The system features 15 channel analog input capability and offers selectable sampling rages of 2, 4, 8, 16, 32, 64, and 128 samples per second. By appropriately jumpering the analog input pins, the sampling rate may be increased by a factor of 5.

The PCM system incorporates a crystal oscillator, and associated CMOS integrated circuitry to develop the clocking pulses, and a 16 channel CMOS analog multiplexer, a 16 channel, 12 bit CMOS analog to digital converter and associated circuitry to provide the pulse coding. The crystal clock oscillator operating at a frequency of 24.576 kHz produces a square wave output with a loss rate of 1 bit in 10^6. The clock pulses gate the analog multiplexer, analog to digital converter and associated follow on circuitry that form the pulse code words. The basic output is a Bi-phased pulse coded signal.

The data is organized in frames. Each frame is headed by a sync code word which is followed sequentially by the pulse coded samples from PCM channels 1 through 15. The sync code word is a pulse coded digital word with a decimal value between 0 and 4095. This word is preselected and hardwired on the circuit board. This code word is essential to the decoding process.

In the initial operation of this system, a sampling rate of 32 samples per second was utilized. Only one sample per coil per frame was analyzed, making use of PCM channels 2, 3, and 4 only.

e. Transmission and Recording

After the data has been PCM encoded, it is transmitted by a VHF radio link back to a receiver located at the Naval Postgraduate School, where it is currently recorded on an instrumentation tape recorder for later analysis.

2. Data Analysis Equipment

Currently, the recorded PCM data is played back into a PCM decoder and associated equipment which generates a nine-track 800 BPI computer tape containing the decoded sensor data. This computer tape is then input into the Naval Postgraduate School IBM 3033 computer for analysis. It is in the computer software that the sensor system transfer function is applied, spectral analysis performed, and the MAD index generated.

B. DATA ANALYSIS SOFTWARE

As was noted earlier, a mainframe computer was utilized to perform the spectral analysis, apply the transfer function, convert to power spectral density, plot the PSD and generate the RMS noise amplitude MAD index (using equation 4-1). This program is written in FORTRAN IV and is discussed in brief below. A copy of the program can be found in Appendix A.

The main program is divided into sections which perform the following functions:

- Data input
- Fourier analysis of time series data

-Application of system transfer function
-Projection of field components onto total field vector
-Data averaging
-Curve fitting and calculation of MAD index
-Calculation and plotting of power spectral density

1. Data Input

Data input is accomplished with the aid of a subroutine package supplied by Dr. Tim Stanton of the Naval Postgraduate School Department of Oceanography. His subroutine (called 'SUBROUTINE RD') serves as a FORTRAN 'READ' statement, taking the PCM data off the computer tape and converting it into integer format with a value between 0 and 4095. The data input section of the main program takes this integer value and converts it to a 'REAL' number and normalizes it to represent a voltage value between -5.0 and +5.0 volts. This section also sorts the input data matching the PCM channel to the data array representing the appropriate coil.

2. Fourier Analysis

The time series data is next converted to the frequency domain by utilizing a subroutine (called 'FOURT') which performs a Fast Fourier Transform (FFT). The subroutine is one available to users at the Naval Postgraduate School and utilizes the Cooley-Tukey FFT algorithm. Further information about this subroutine can be found in the program listing in Appendix A.

3. Application of Transfer Function and Total Field Projection

The next section of code applies the system transfer functions for the three coils to the frequency domain data.

The transfer functions are given as straight line segments which were found by least-squares approximation. The data enters this section in amplitude units of volts, and is converted into nanoTeslas by the transfer function.

Following the application of the system transfer function to the coil data, the program next calculates the projection of this data onto the earth's magnetic field vector (total field projection). This is done by first applying the local magnetic variation (declination) to the North-South (X) and East-West (Y) coil information to determine the horizontal field component. The local magnetic dip (inclination) angle is then used to project the vertical (Z-coil) and horizontal field fluctuations onto the total field fluctuation.

4. Data Averaging

The previous program sections exist inside of a do-loop which enables the analysis of a long period of data without a prohibitive need for storage space. This loop includes accumulator arrays for each field component and the total field projection. The fluctuation data is converted into power prior to storage. This is done by taking the magnitude of the fluctuation component, dividing by the number of sample points, and then squaring the value. After the program passes through the averaging loop for the last time, the arithmetic average is taken for each frequency point on the arrays. At his stage the power spectrum is multiplied by the sample period to determine power spectral density.

5. MAD Index Calculation

The next section computes the RMS MAD noise index previously discussed. A polynomial curve fit is performed on

the total field PSD using an available subroutine ('CHBFT'). The resulting polynomial is then integrated over the limits of the various ASQ-81 band pass settings.

6. Plotting of Power Spectral Density

Plots of the power spectral density of each of the field components and the total field projection are generated in the last section of the program. This is done by converting the fluctuation power spectral density to decibels (dB) referenced to 1 nanoTesla^2 per Hertz. A Versatec plotting subroutine ('PLOTP') is then called to actually generate the plots.

C. INITIAL SYSTEM OPERATION

The NPS MAD index system was initially placed into operation with the coil sensors located in the La Mesa Village housing area near the Naval Postgraduate School, Monterey, California. System checkout was accomplished in June, 1982. The full system was placed into operation on 25 July 1982 and 18 August 1982 in conjunction with similar measurements taken on the floor of Monterey Bay.

The MAD index output and power spectral density plots of the total field fluctuation for 25 July 1982, 1237-1406 local (2037-2206Z), and 18 August 1982, 0121-0250 local (0921-1050Z) and 0507-0636 local (1307-1436Z) are shown in Tables IX, X, XI, and Figures 5.4, 5.5, and 5.6 respectively.

TABLE IX

MAD Noise 2037-2206Z, 25 JUL 82, Monterey, CA

1 Gamma = 1 NanoTesla

```
MAD INDEX=        0.1083  GAMMAS
BANDPASS:    0.04  TO  0.20 HERTZ

MAD INDEX=        0.1148  GAMMAS
BANDPASS:    0.04  TO  0.40 HERTZ

MAD INDEX=        0.1169  GAMMAS
BANDPASS:    0.04  TO  0.60 HERTZ

MAD INDEX=        0.0888  GAMMAS
BANDPASS:    0.06  TO  0.20 HERTZ

MAD INDEX=        0.0966  GAMMAS
BANDPASS:    0.06  TO  0.40 HERTZ

MAD INDEX=        0.0991  GAMMAS
BANDPASS:    0.06  TO  0.60 HERTZ

MAD INDEX=        0.0729  GAMMAS
BANDPASS:    0.08  TO  0.20 HERTZ

MAD INDEX=        0.0822  GAMMAS
BANDPASS:    0.08  TO  0.40 HERTZ

MAD INDEX=        0.0852  GAMMAS
BANDPASS:    0.08  TO  0.60 HERTZ

MAD INDEX=        0.0598  GAMMAS
BANDPASS:    0.10  TO  0.20 HERTZ

MAD INDEX=        0.0708  GAMMAS
BANDPASS:    0.10  TO  0.40 HERTZ

MAD INDEX=        0.0743  GAMMAS
BANDPASS:    0.10  TO  0.60 HERTZ

MAD INDEX=        0.1234  GAMMAS
BANDPASS:    0.04  TO  2.00 HERTZ

MAD INDEX=        0.1122  GAMMAS
BANDPASS:    0.06  TO  2.00 HERTZ

MAD INDEX=        0.1018  GAMMAS
BANDPASS:    0.08  TO  2.00 HERTZ

MAD INDEX=        0.0923  GAMMAS
BANDPASS:    0.10  TO  2.00 HERTZ
```

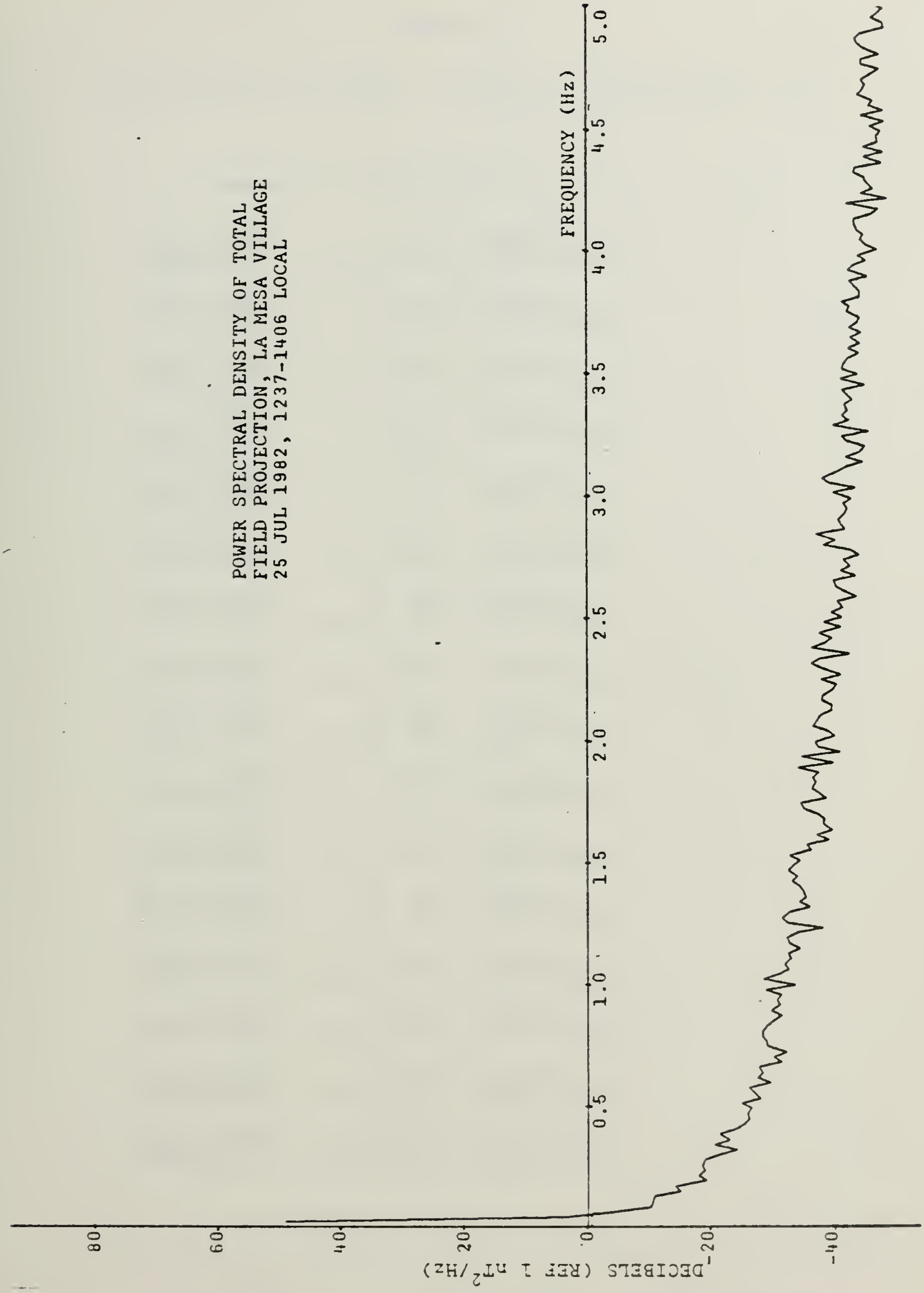


Figure 5.4 PSD 25 JUL 82, 2037-2206Z, La Mesa Village

TABLE X

MAD Noise 0921-1050Z, 18 AUG 82, Monterey, CA

```
    1 Gamma = 1 NanoTesla

 MAD INDEX=      0.3644 GAMMAS
 BANDPASS:   0.04 TO  0.20 HERTZ

 MAD INDEX=      0.3960 GAMMAS
 BANDPASS:   0.04 TO  0.40 HERTZ

 MAD INDEX=      0.4004 GAMMAS
 BANDPASS:   0.04 TO  0.60 HERTZ

 MAD INDEX=      0.3027 GAMMAS
 BANDPASS:   0.06 TO  0.20 HERTZ

 MAD INDEX=      0.3401 GAMMAS
 BANDPASS:   0.06 TO  0.40 HERTZ

 MAD INDEX=      0.3453 GAMMAS
 BANDPASS:   0.06 TO  0.60 HERTZ

 MAD INDEX=      0.2528 GAMMAS
 BANDPASS:   0.08 TO  0.20 HERTZ

 MAD INDEX=      0.2966 GAMMAS
 BANDPASS:   0.08 TO  0.40 HERTZ

 MAD INDEX=      0.3025 GAMMAS
 BANDPASS:   0.08 TO  0.60 HERTZ

 MAD INDEX=      0.2118 GAMMAS
 BANDPASS:   0.10 TO  0.20 HERTZ

 MAD INDEX=      0.2624 GAMMAS
 BANDPASS:   0.10 TO  0.40 HERTZ

 MAD INDEX=      0.2691 GAMMAS
 BANDPASS:   0.10 TO  0.60 HERTZ

 MAD INDEX=      0.4047 GAMMAS
 BANDPASS:   0.04 TO  2.00 HERTZ

 MAD INDEX=      0.3679 GAMMAS
 BANDPASS:   0.06 TO  2.00 HERTZ

 MAD INDEX=      0.3339 GAMMAS
 BANDPASS:   0.08 TO  2.00 HERTZ

 MAD INDEX=      0.3026 GAMMAS
 BANDPASS:   0.10 TO  2.00 HERTZ
```

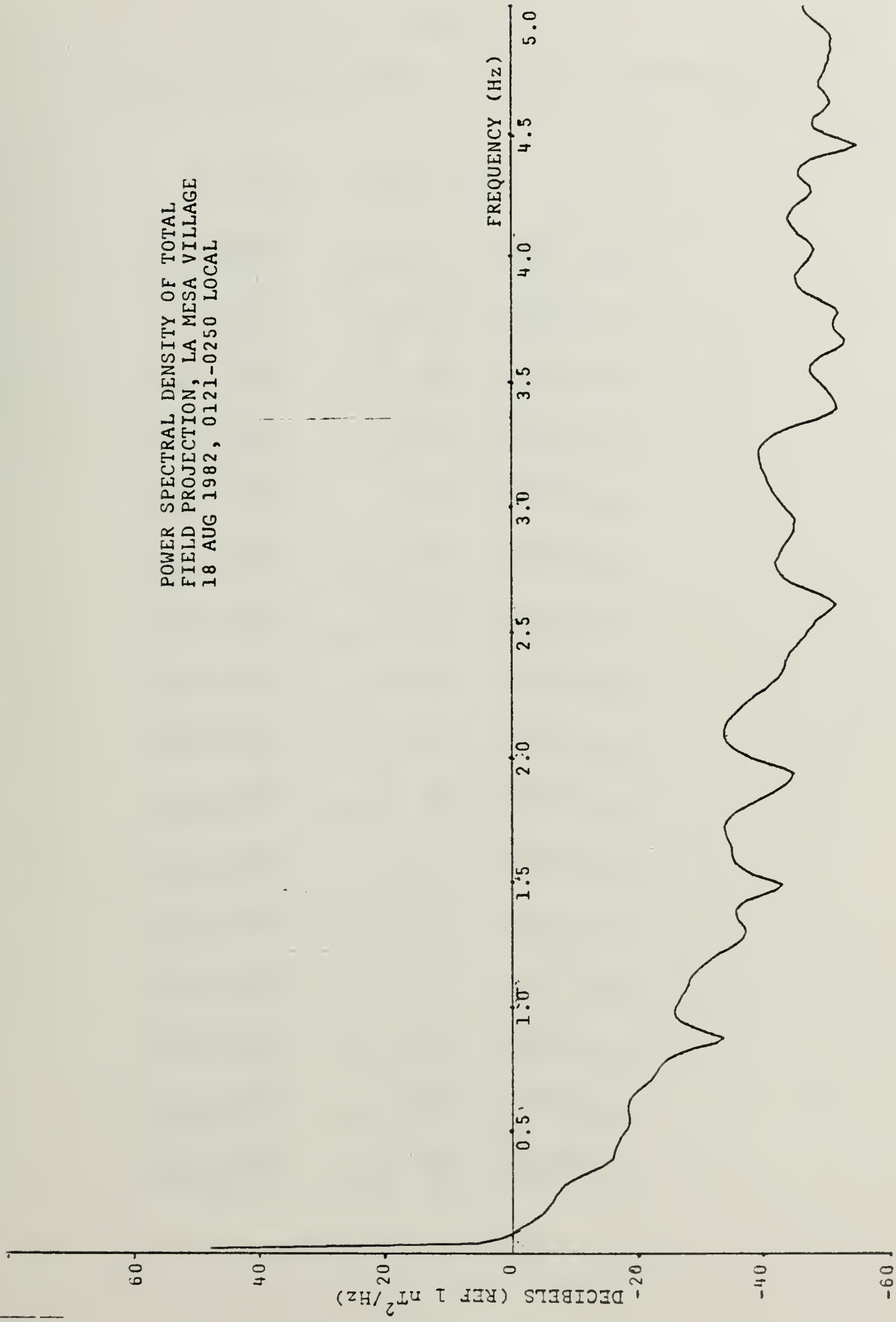


Figure 5.5 PSD 18 AUG 82, 0921-1050Z, La Mesa Village

TABLE XI

MAD Noise 1307-1436Z, 18 AUG 82, Monterey, CA

```
    1 Gamma = 1 NanoTesla

MAD INDEX=       0.3188 GAMMAS
BANDPASS:    0.04 TO  0.20 HERTZ

MAD INDEX=       0.3246 GAMMAS
BANDPASS:    0.04 TO  0.40 HERTZ

MAD INDEX=       0.3267 GAMMAS
BANDPASS:    0.04 TO  0.60 HERTZ

MAD INDEX=       0.2297 GAMMAS
BANDPASS:    0.06 TO  0.20 HERTZ

MAD INDEX=       0.2376 GAMMAS
BANDPASS:    0.06 TO  0.40 HERTZ

MAD INDEX=       0.2405 GAMMAS
BANDPASS:    0.06 TO  0.60 HERTZ

MAD INDEX=       0.1585 GAMMAS
BANDPASS:    0.08 TO  0.20 HERTZ

MAD INDEX=       0.1698 GAMMAS
BANDPASS:    0.08 TO  0.40 HERTZ

MAD INDEX=       0.1738 GAMMAS
BANDPASS:    0.08 TO  0.60 HERTZ

MAD INDEX=       0.1031 GAMMAS
BANDPASS:    0.10 TO  0.20 HERTZ

MAD INDEX=       0.1199 GAMMAS
BANDPASS:    0.10 TO  0.40 HERTZ

MAD INDEX=       0.1254 GAMMAS
BANDPASS:    0.10 TO  0.60 HERTZ

MAD INDEX=       0.3504 GAMMAS
BANDPASS:    0.04 TO  2.00 HERTZ

MAD INDEX=       0.3137 GAMMAS
BANDPASS:    0.06 TO  2.00 HERTZ

MAD INDEX=       0.2801 GAMMAS
BANDPASS:    0.08 TO  2.00 HERTZ

MAD INDEX=       0.2495 GAMMAS
BANDPASS:    0.10 TO  2.00 HERTZ
```

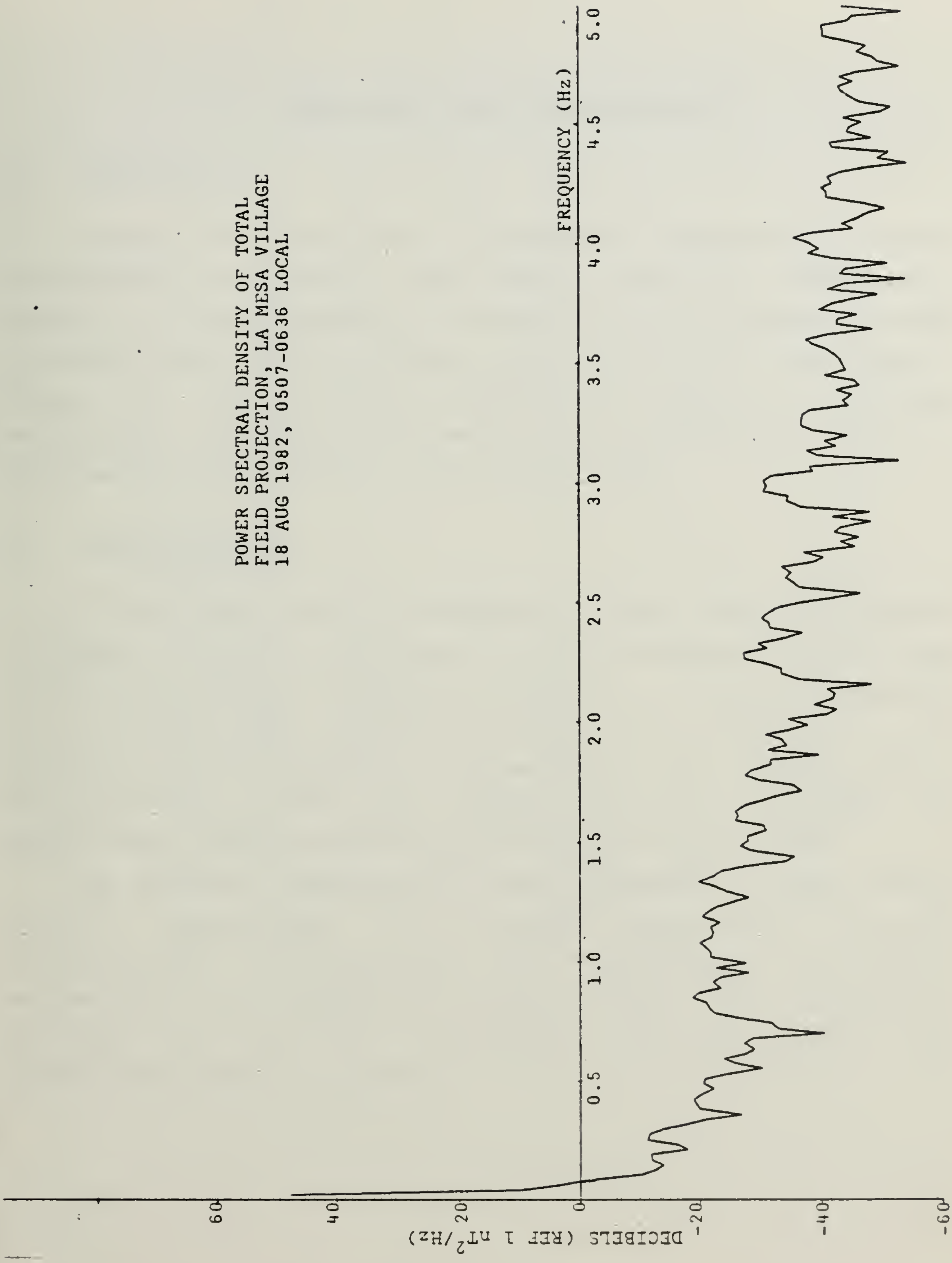


Figure 5.6 PSD 18 AUG 82, 1307-1436Z, La Mesa Village

VI. CONCLUSION AND RECOMMENDATIONS

A. CONCLUSION

Analysis of available information regarding current geomagnetic indices and the actual level of geomagnetic noise in the MAD bandpass indicates that the currently used indices, the K and Ap indices, are not valid for MAD operations. It is therefore desirable to derive a new index which more accurately represents the geomagnetic noise at frequencies of interest in MAD operations.

B. RECOMMENDATIONS

A tentative index was developed, tested, and sample data obtained. The data analysis for the preliminary system was accomplished using a mainframe computer. It is recommended that further work include improving the index and the setting up of a system to on-line decode the incoming data, and utilizing a desk top computer such as the HP9845 to enable real time determination of the MAD noise index.

The spatial coherence of MAD geomagnetic noise should also be investigated, with possible application to noise cancellation. Additionally, the feasibility of the prior estimation of geomagnetic noise should be evaluated, possibly by using the prediction methods proposed by Fraser-Smith [Ref. 42, 43].

APPENDIX A

MAD INDEX DATA ANALYSIS SOFTWARE

```
//JEFF$1L JOB (3224,0129),'SCHWEIGER SMC 2239',CLASS=F                  MAD00060
//*MAIN ORG=NPGVM1.3224P,LINES=(10)                                     MAD00070
//*FORMAT PR,DDNAME=PLOT.SYSVECTR,DEST=LOCAL                            MAD00080
// EXEC FRTXCLGP,PARM.LKED='LIST,MAP,XREF',REGION.GO=1200K              MAD00090
//FORT.SYSIN DD *                                                       MAD00100
      INTEGER*2 IN(16)                                                  MAD00110
C      ARRAY 'IN' IS USED IN READING DATA FROM TAPE                     MAD00120
      COMPLEX*8 XX(9500),YY(9500),ZZ(9500),TF(9500)                     MAD00130
C      THE COMPLEX*8 ARRAYS ARE USED TO ORDER INPUT DATA AND INITIALLY  MAD00140
C      REPRESENT VOLTAGE - TIME SERIES INFORMATION.                     MAD00150
      DIMENSION TIME(9500),FREQ(9500),WORK(19000),FRQ2(500)             MAD00160
      DIMENSION ZX(9500),ZY(9500),ZV(9500),ZT(9500)                     MAD00170
C      THE 'Z' ARRAYS REPRESENT FREQUENCY DOMAIN (FF TRANSFORMED)       MAD00180
C      MAGNITUDE DATA AND ARE EVENTUALLY CONVERTED TO POWER SPECTRAL    MAD00190
C      DENSITY INFORMATION.                                             MAD00200
      INTEGER R(10)                                                     MAD00210
      DIMENSION RX(10),RH(10),PX1(94),PY1(94),PC(10),PD(9),PX(40),PY(40)MAD00220
C      THE 'R' AND 'P' ARRAYS ARE USED IN CURVE FITTING THE             MAD00230
C      POWER SPECTRAL DENSITY OF THE ACTIVITY PROJECTION ON THE         MAD00240
C      TOTAL FIELD.                                                     MAD00250
      DIMENSION FL(4),FU(4)                                             MAD00260
      INTEGER*4 ITB(12)/12*0/                                           MAD00270
      REAL*4    RTB(28)/28*0.0/                                         MAD00280
      REAL ALAB(4)/'CH-X','CH-Y','CH-Z','TOT'/                          MAD00290
      REAL*8 TITLE(12)                                                  MAD00300
      EQUIVALENCE(TITLE(1),RTB(5))                                      MAD00310
C      ARRAYS 'ITB','RTB','ALAB',AND 'TITLE' ARE USED IN GENERATING     MAD00320
C      THE VERTSATEC PLOTTER OUTPUT.                                    MAD00330
      DATA XX,YY,ZZ,TF/38000*(0.,0.)/                                   MAD00340
      DATA ZX,ZY,ZV,ZT/38000*0./                                        MAD00350
      DATA FL/.04,.06,.08,.1/                                           MAD00360
      DATA FU/.2,.4,.6,2./                                              MAD00370
      DATA TIME,FREQ/19000*0./                                          MAD00380
      DATA PX,PY,PX1,PY1/268*0./                                        MAD00390
      TWOPI=6.2831853                                                   MAD00400
      COS60=COS(TWOPI/6.)                                               MAD00410
      COS30=COS(TWOPI/12.)                                              MAD00420
      D=16.75*TWOPI/360.                                                MAD00430
      COSD=COS(D)                                                       MAD00440
      COSD1=COS((90. - D)*TWOPI/360.)                                   MAD00450
C       D IS THE DECLINATION OR MAGNETIC VARIATION AT THE MAGNETOMETER  MAD00460
C       SITE.                                                           MAD00470
C       THE NEXT FIVE LINES SERVE AS A TIME DELAY IN STARTING THE       MAD00480
C       DATA ANALYSIS                                                   MAD00490
      ISEC=3                                                            MAD00500
      ITL=ISEC*32                                                       MAD00510
      DO 55 JJ=1,ITL                                                    MAD00520
      CALL RD(20,IN,1000,IREC,IRR)                                      MAD00530
```

```
   55 CCNTINUE                                                          MAD00540
      IFRAME=9500                                                       MAD00550
      NR=18                                                             MAD00560
      FNR=FLOAT(NR)                                                     MAD00570
      DC 70 L1=1,NR                                                     MAD00580
C       THE DO LOOP ENDING WITH STATEMENT 70 ENABLES THE PROGRAM TO     MAD00590
C       PROCESS A LARGE AMOUNT OF DATA BY REPEATING THE PROCESS IN      MAD00600
C       BLOCKS. THE DATA POINTS FROM EACH RUN THROUGH THE DC LOOP ARE   MAD00610
C       ADDED TOGETHER AND EVENTUALLY AVERAGED BY THE NUMBER OF RUNS    MAD00620
C       THROUGH THE DO LOOP.                                            MAD00630
C       'NR' REPRESENTS THE NUMBER OF DATA SEQUENCES TO BE AVERAGED.    MAD00640
C       1 SEQUENCE CURRENTLY EQUALS 9500 DATA POINTS FOR EACH CHANNEL   MAD00650
C       OR 296.88 SECONDS OF DATA.                                      MAD00660
C                                                                       MAD00670
C        THE DO LOCP ENDING WITH 60 READS THE DATA FROM THE PCM FRAME   MAD00680
C        STRIPS OUT THE SYNC CODE, AND SORTS OUT THE DATA BY COIL       MAD00690
C        CHANNEL                                                        MAD00700
      DO 60 JJ=1,IFRAME                                                 MAD00710
      CALL RD(20,IN,1000,IREC,IRR)                                      MAD00720
      XX(JJ)=IN(2)                                                      MAD00730
      YY(JJ)=IN(3)                                                      MAD00740
      ZZ(JJ)=IN(4)                                                      MAD00750
   6C CONTINUE                                                          MAD00760
      WRITE(6,200)IRR,IREC                                              MAD00770
  200 FORMAT(10X,'IRR=',I6,5X,'IREC=',I6,/)                             MAD00780
C        THE FOLLOWING SECTION GENERATES THE TIME AND FREQUENCY         MAD00790
C        ARRAYS AND NORMALIZES THE INPUT PCM DATA TO VOLTAGE FORM       MAD00800
C        IN PREPARATION FOR FAST FOURIER TRANSFORM TC THE FREQUENCY     MAD00810
C        DOMAIN.                                                        MAD00820
      N=9500                                                            MAD00830
      FN=FLCAT(N)                                                       MAD00840
      DELTAT=1./32.                                                     MAD00850
      T=FN*DELTAT                                                       MAD00860
      DELTAF=TWOPI/(FN*DELTAT)                                          MAD00870
      DC 20 J=1,N                                                       MAD00880
      TIME(J)=DELTAT*FLCAT(J)                                           MAD00890
      FREQ(J)=DELTAF*FLOAT(J)                                           MAD00900
      XX(J)=(XX(J)-2048.)*5./2048.                                      MAD00910
      XX(J)=REAL(XX(J))                                                 MAD00920
      YY(J)=(YY(J)-2048.)*5./2048.                                      MAD00930
      YY(J)=REAL(YY(J))                                                 MAD00940
      ZZ(J)=(ZZ(J)-2048.)*5./2048.                                      MAD00950
      ZZ(J)=REAL(ZZ(J))                                                 MAD00960
C        'XX' IS THE X-CCIL DATA, 'YY' IS THE Y-CCIL DATA,              MAD00970
C        'ZZ' IS THE Z-COIL DATA, AND 'TF' IS THE PRCJECTICN OF THE     MAD00980
C        NCRTH-SCUTH COMPONENT (XX) AND THE VERTICAL COMPONENT (ZZ)     MAD00990
C        ON THE TOTAL GEOMAGNETIC FIELD VECTOR.                         MAD01000
   20 CONTINUE                                                          MAD01010
```

```
      DO 21 J=1,500                                                     MAD01020
      FRQ2(J)=ALOG10(FREQ(J))                                           MAD01030
   21 CONTINUE                                                          MAD01040
C       THE NEXT FOUR STATEMENTS PERFORM AN FFT ON THE INPUT            MAD01050
C       TIME SERIES DATA. SEE THE WRITEUP ON 'FOURT' FOR                MAD01060
C       FURTHER INFORMATION.                                            MAD01070
      CALL FOURT(XX,N,1,-1,0,WORK)                                      MAD01080
      CALL FOURT(YY,N,1,-1,0,WORK)                                      MAD01090
      CALL FOURT(ZZ,N,1,-1,0,WORK)                                      MAD01100
C      THE NEXT BLOCK OF STATEMENTS APPLY THE SYSTEM (VOLTAGE TO        MAD01110
C      B-FIELD) TRANSFER FUNCTION TO THE TRANSFORMED FREQUENCY          MAD01120
C      DOMAIN DATA.  THIS BLOCK ENDS AT STATEMENT 9.                    MAD01130
C      THE TRANSFER FUNCTION CONVERTS VOLTS TO NANOTESLAS (GAMMAS).     MAD01140
C      ***WARNING*** THIS TRANSFER FUNCTIONS YIELDS AN INACCURATE       MAD01150
C      PHASE.  USE A DIFFERENT TRANSFER FUNCTION IF PHASE INFORMATION   MAD01160
C      NEEDED.                                                          MAD01170
      DO 9 L=1,N                                                        MAD01180
      FRQ=FREQ(L)                                                       MAD01190
      IF(FRQ.LE.25.)GO TO 1                                             MAD01200
      XX(L)=XX(L)/28.                                                   MAD01210
      GO TO 8                                                           MAD01220
    1 IF(FRQ.LE.15.)GO TO 2                                             MAD01230
      XX(L)=XX(L)/(105.5-3.14*FRQ)                                      MAD01240
      YY(L)=YY(L)/(181.32-7.588*FRQ)                                    MAD01250
      ZZ(L)=ZZ(L)/(177.26-7.484*FRQ)                                    MAD01260
      GO TO 8                                                           MAD01270
    2 IF(FRQ.LE.10.)GO TO 3                                             MAD01280
      XX(L)=XX(L)/(5.958*FRQ-30.97)                                     MAD01290
      YY(L)=YY(L)/(7.166*FRQ-39.99)                                     MAD01300
      ZZ(L)=ZZ(L)/(6.49*FRQ-32.35)                                      MAD01310
      GO TO 8                                                           MAD01320
    3 IF(FRQ.LE.7.5)GO TO 4                                             MAD01330
      XX(L)=XX(L)/(3.492*FRQ-6.31)                                      MAD01340
      YY(L)=YY(L)/(4.252*FRQ-10.85)                                     MAD01350
      ZZ(L)=ZZ(L)/(4.044*FRQ-7.89)                                      MAD01360
      GO TO 8                                                           MAD01370
    4 IF(FRQ.LE.5.)GO TO 5                                              MAD01380
      XX(L)=XX(L)/(2.6311*FRQ+0.14667)                                  MAD01390
      YY(L)=YY(L)/(3.012*FRQ-1.55)                                      MAD01400
      ZZ(L)=ZZ(L)/(3.184*FRQ-1.44)                                      MAD01410
      GO TO 8                                                           MAD01420
    5 IF(FRQ.LE.3.)GO TO 6                                              MAD01430
      XX(L)=XX(L)/(2.6311*FRQ+0.14667)                                  MAD01440
    7 YY(L)=YY(L)/(2.702*FRQ)                                           MAD01450
      ZZ(L)=ZZ(L)/(2.92*FRQ)                                            MAD01460
      GO TO 8                                                           MAD01470
    6 XX(L)=XX(L)/(2.72*FRQ)                                            MAD01480
      GO TO 7                                                           MAD01490
```

```
    8 CONTINUE                                                           MAD01500
      TF(L)=(XX(L)*COSD + YY(L)*COSD1)*COS60 + ZZ(L)*COS30               MAD01510
    9 CONTINUE                                                           MAD01520
C      IN THE NEXT BLOCK, ENDING WITH 30, THE MAGNITUDE OF THE COMPLEX   MAD01530
C      FREQUENCY DOMAIN DATA IS TAKEN AND PLACED IN A REAL ARRAY. 'ZX'   MAD01540
C      FOR THE X-COIL, 'ZY' FOR THE Y-COIL, 'ZV' FOR THE Z OR VERTICAL   MAD01550
C      COIL AND 'ZT' FOR THE TOTAL FIELD PROJECTION. THIS DATA IS        MAD01560
C      DIVIDED BY THE NUMBER OF SAMPLE POINTS AND SQUARED TO DETERMINE   MAD01570
C      POWER.                                                            MAD01580
      DO 30 I1=1,N                                                       MAD01590
      ZX(I1)=ZX(I1)+(CABS(XX(I1))/FN)**2                                 MAD01600
      ZY(I1)=ZY(I1)+(CABS(YY(I1))/FN)**2                                 MAD01610
      ZV(I1)=ZV(I1)+(CABS(ZZ(I1))/FN)**2                                 MAD01620
      ZT(I1)=ZT(I1)+(CABS(TF(I1))/FN)**2                                 MAD01630
   30 CONTINUE                                                           MAD01640
   70 CONTINUE                                                           MAD01650
C      THE FOLLOWING BLOCK AVERAGES THE DATA POINTS ADDED IN BLOCK 30    MAD01660
C      ABOVE BY THE NUMBER OF RUNS THROUGH THE DO LOOP ENDING WITH 70.   MAD01670
C      AT THIS POINT THE POWER CURVES ARE CONVERTED INTO POWER SPECTRAL MAD01680
C      DENSITY.                                                          MAD01690
      DO 33 I3=1,N                                                       MAD01700
      ZX(I3)=ZX(I3)*T/FNR                                                MAD01710
      ZY(I3)=ZY(I3)*T/FNR                                                MAD01720
      ZV(I3)=ZV(I3)*T/FNR                                                MAD01730
      ZT(I3)=ZT(I3)*T/FNR                                                MAD01740
   33 CONTINUE                                                           MAD01750
C      THE NEXT STATEMENTS, THROUGH 204, ARE USED IN CURVE FITTING       MAD01760
C      THE POWER SPECTRAL DENSITY OF THE TOTAL FIELD PROJECTION          MAD01770
C      AND IN CALCULATING A MAD ACTIVITY INDEX.                          MAD01780
      DO 37 I=3,42                                                       MAD01790
      PX(I-2)=FREQ(I)                                                    MAD01800
      PY(I-2)=ZT(I)                                                      MAD01810
   37 CONTINUE                                                           MAD01820
      M2=8                                                               MAD01830
      M3=9                                                               MAD01840
      WRITE(6,201)                                                       MAD01850
  201 FORMAT('1')                                                        MAD01860
      CALL CHBFT(PX,PY,40,PC,M2,RX,RH,R)                                 MAD01870
      DO 38 I=1,M3                                                       MAD01880
      PD(I)=PC(I)/FLOAT(I)                                               MAD01890
   38 CONTINUE                                                           MAD01900
      DO 39 K=1,4                                                        MAD01910
      DO 46 LL=1,3                                                       MAD01920
      XU=0.                                                              MAD01930
      XL=0.                                                              MAD01940
      DO 47 I=1,9                                                        MAD01950
      XU=XU+PD(I)*(FU(LL)**I)                                            MAD01960
      XL=XL+PD(I)*(FL(K)**I)                                             MAD01970
```

```
 47 CONTINUE                                                                  MAD01980
    IF(XU.LE.XL )GO TO 71                                                     MAD01990
    GO TO 72                                                                  MAD02000
 71 M2=M2-1                                                                   MAD02010
    M3=M3-1                                                                   MAD02020
    CALL CHBFT(PX,PY,40,PC ,M2 ,RX,RH,R)                                      MAD02030
    DO 73 I=1,M3                                                              MAD02040
    PD(I)=PC(I)/FLOAT(I)                                                      MAD02050
 73 CONTINUE                                                                  MAD02060
    XU=0.                                                                     MAD02070
    XL=0.                                                                     MAD02080
    DO 74 I=1,M3                                                              MAD02090
    XU=XU+PD(I)*(FU(LL)**I)                                                   MAD02100
    XL=XL+PD(I)*(FL(K)**I)                                                    MAD02110
 74 CONTINUE                                                                  MAD02120
 72 XMI=SQRT(XU-XL)                                                           MAD02130
    WRITE(6,204)XMI,FL(K),FU(LL)                                              MAD02140
204 FORMAT(10X,'MAD INDEX= ',F10.4,1X,'GAMMAS',/,10X,'BANDPASS:',2X,          MAD02150
   1 F5.2,' TO ',F5.2,' HERTZ',/)                                             MAD02160
 45 CONTINUE                                                                  MAD02170
 39 CONTINUE                                                                  MAD02180
    DO 31 I=3,96                                                              MAD02190
    PX1(I-2)=FREQ(I)                                                          MAD02200
    PY1(I-2)=ZT(I)                                                            MAD02210
 31 CONTINUE                                                                  MAD02220
    M2=8                                                                      MAD02230
    M3=9                                                                      MAD02240
    CALL CHBFT(PX1,PY1,94,PC,M2,RX,RH,R)                                      MAD02250
    DO 34 I=1,M3                                                              MAD02260
    PD(I)=PC(I)/FLOAT(I)                                                      MAD02270
 34 CONTINUE                                                                  MAD02280
    DO 35 K=1,4                                                               MAD02290
    XU=0.                                                                     MAD02300
    XL=0.                                                                     MAD02310
    DO 36 I=1,9                                                               MAD02320
    XU=XU+PD(I)*(FU(4)**I)                                                    MAD02330
    XL=XL+PD(I)*(FL(K)**I)                                                    MAD02340
 36 CONTINUE                                                                  MAD02350
    IF(XU.LE.XL )GO TO 75                                                     MAD02360
    GO TO 76                                                                  MAD02370
 75 M2=M2-1                                                                   MAD02380
    M3=M3-1                                                                   MAD02390
    CALL CHBFT(PX1,PY1,94,PC,M2,RX,RH,R)                                      MAD02400
    DO 77 I=1,M3                                                              MAD02410
    PD(I)=PC(I)/FLOAT(I)                                                      MAD02420
    IM=I-1                                                                    MAD02430
 77 CONTINUE                                                                  MAD02440
    XU=0.                                                                     MAD02450
```

```
      XL=0.                                                             MAD02460
      DO 78 I=1,M3                                                      MAD02470
      XU=XL+PD(I)*(FU(4)**I)                                            MAD02480
      XL=XL+PD(I)*(FL(K)**I)                                            MAD02490
   78 CONTINUE                                                          MAD02500
   76 XMI=SQRT(XU-XL)                                                   MAD02510
      WRITE(6,204)XMI,FL(K),FU(4)                                       MAD02520
   35 CONTINUE                                                          MAD02530
C       THE NEXT DO LOOP CONVERTS THE B-FIELD POWER SPECRAL DENSITY     MAD02540
C       INTO DECIBELS REFERENCED TO 1 NANOTESLA (GAMMA) **2/HERTZ.      MAD02550
      DO 32 I=1,N                                                       MAD02560
      ZX(I)=10.*ALOG10( ZX(I))                                          MAD02570
      ZY(I)=10.*ALOG10( ZY(I))                                          MAD02580
      ZV(I)=10.*ALOG10( ZV(I))                                          MAD02590
      ZT(I)=10.*ALOG10( ZT(I))                                          MAD02600
   32 CONTINUE                                                          MAD02610
C                                                                       MAD02620
C    VERSATEC PLOT OF B - FIELD SPECTRA                                 MAD02630
C                                                                       MAD02640
      NPTS=10./DELTAF +1.                                               MAD02650
      NPD2=NPTS/2 +1                                                    MAD02660
C        'NPTS' DETERMINES NUMBER OF POINTS NECESSARY IN ORDER FOR      MAD02670
C         THE 0 TO 10 HERTZ RANGE TO BE PLOTTED.                        MAD02680
C        'NPD2' IS FOR THE 0 TO 5 HERTZ RANGE.                          MAD02690
C        FOR THE FOLLOWING 'ITB' AND 'RTB' VALUES REVIEW THE WRITE-UP   MAD02700
C        FOR THE SUBROUTINE PROCEDURE 'DRAWP'.                          MAD02710
      ITB(3)=20                                                         MAD02720
      ITB(4)=8                                                          MAD02730
      ITB(12)=0                                                         MAD02740
      RTB(1)=0.0                                                        MAD02750
      RTB(2)=0.0                                                        MAD02760
      RTB(3)=ALAB(1)                                                    MAD02770
      READ(5,3000)TITLE                                                 MAD02780
      CALL DRAWP(NPTS,FRQ2,ZX,ITB,RTB)                                  MAD02790
      RTB(3)=ALAB(2)                                                    MAD02800
      READ(5,3000)TITLE                                                 MAD02810
      CALL DRAWP(NPTS,FRQ2,ZY,ITB,RTB)                                  MAD02820
      RTB(3)=ALAB(3)                                                    MAD02830
      READ(5,3000)TITLE                                                 MAD02840
      CALL DRAWP(NPTS,FRQ2,ZV,ITB,RTB)                                  MAD02850
      ITB(3)=10                                                         MAD02860
      ITB(12)=1                                                         MAD02870
      RTB(3)=ALAB(4)                                                    MAD02880
      READ(5,3000)TITLE                                                 MAD02890
      CALL DRAWP(NPD2,FREQ,ZT,ITB,RTB)                                  MAD02900
 3000 FORMAT(6A8)                                                       MAD02910
      STOP                                                              MAD02920
      END                                                               MAD02930
```

```
      SUBROUTINE RD(IUN,IO,IRS,IREC,IRQ)
C
C        THIS PROCEDURE FURNISHED BY DR. TIM STANTON,
C        DEPARTMENT OF OCEANOGRAPHY.
C
C             READ DATA FROM IUN, ALLIGN , CHECK & RETURN
C
C       IUN=TAPE NUMBER, EG 20
C       IO=INTEGER*2 ARRAY, 16 LONG,(VALUES 0-4095, SUBTRACT 2048)*5
C              /2028.  GIVES VOLTAGE
C       IRS= NUMBER OF RESINCS ALLOWED (ERRORS)
C       IREC= COUNTER OF RECORDS (FRAMES OF DATA)
C           BLOCK 512 BITS,   32 BITS = RECORD
C           800 BPI TAPE UNLABLED
C       IRQ= NUMBER OF ACTUAL RESINCS (ERRORS)
C
C
      INTEGER * 2 IO(16),IP(16)
      DATA IRR /0/
      IF (IREC.EQ.0) IS=0
      IER=0
 20   FORMAT (16A2)
      IF (IS.NE.0) GO TO 50
      READ (IUN,20,END=900) IP
      IREC=IREC+1
 40   IS=IS+1
      IF (IS.LT.17) GO TC 50
      READ (IUN,20,END=900) IP
     IS=1
     IREC=IREC+1
 50  ICH=IMASK(IP(IS),3,0)+1
C     WRITE (6,55) ICH,IS,IUN,IREC
 55   FORMAT ('  RESYNCING ICH,IS,IUN,IREC ',4I8)
C
     IF (ICH.NE.1) GO TC 40
     DO 100 I=1,16
      IO(I)=ISHIFT( IP( IS),4)
     ICH=IMASK(IP(IS),3,0)+1
     IF (ICH.EQ.I) GO TO 80
     IER=IER+1
     WRITE (6,70)  IUN,IREC ,I,ICH,IER
 70   FORMAT (' UNIT ',I3,' RECORD ',I6,'CHAN & DATA CH ',2I4,
    $ 'ERRORS ',I7)
 80   IS=IS+1
      IF (IS.LT.17) GO TO 100
      READ (IUN,20,END=900) IP
      IS=1
      IREC=IREC+1
```

```
 100  CONTINUE                                                          MADO3420
C                                                                       MADO3430
      IF (IER.EQ.0) GO TO 150                                           MADO3440
      IRR=IRR+1                                                         MADO3450
      IF (IRR.LT.IRS) GO TO 120                                         MADO3460
      WRITE (6,110)                                                     MADO3470
 110  FORMAT ('1 STOPPED IN SUB RD BECAUSE OF IRR.GT.',I6,' AT L110')   MADO3480
      IRQ=IRR                                                           MADO3490
      STOP                                                              MADO3500
 120  CONTINUE                                                          MADO3510
      WRITE (6,130) IREC,IRR                                            MADO3520
 130  FORMAT (' RESYNC AT FRAME ',I6,' WITH TOTAL ERRORS ',I7)          MADO3530
      IER=0                                                             MADO3540
      IRQ=IRR                                                           MADO3550
      GO TO 50                                                          MADO3560
 150  CONTINUE                                                          MADO3570
      RETURN                                                            MADO3580
 900  WRITE (6,910) IUN,IREC                                            MADO3590
 910  FORMAT ('1    END OF UNIT ',I3,' AT REC ',I7)                     MADO3600
      STOP                                                              MADO3610
      END                                                               MADO3620
                                                                        MADO3630
      FUNCTION ISHIFT (IN,NPLC)                                         MADO3640
C              RETURNS SHIFTED VALUE OF I*2 WORD IN                     MADO3650
C              -VE LEFT,+VE RIGHT SHIFT                                 MADO3660
C                                                                       MADO3670
      INTEGER * 2 IN                                                    MADO3680
      IP=IN                                                             MADO3690
      IF (IP.LT.0) IP=IP+65536                                          MADO3700
      IF (NPLC.LT.0) GO TO 30                                           MADO3710
      ISHIFT=IP/(2**IABS(NPLC))                                         MADO3720
      RETURN                                                            MADO3730
  30  ISHIFT=IP*(2**IABS(NPLC))                                         MADO3740
      IF (ISHIFT.GT.65535) ISHIFT=MOD(ISHIFT,65536)                     MADO3750
      RETURN                                                            MADO3760
      END                                                               MADO3770
      FUNCTION IMASK (IN,IBL,IBR)                                       MADO3780
C              MASK I*2 WORD IN OUTSIDE BITS IBL & IBR                  MADO3790
C                                                                       MADO3800
      INTEGER * 2 IN,IO                                                 MADO3810
      IO=IN                                                             MADO3820
      IF (IBR.EQ.0) GO TO 50                                            MADO3830
      IT=ISHIFT(IN,IBR)                                                 MADO3840
      IO=IT                                                             MADO3850
  50  IP=ISHIFT(IO,IBL-15-IBR)                                          MADO3860
      IO=IP                                                             MADO3870
      IMASK=ISHIFT(IO,15-IBL)                                           MADO3880
      RETURN                                                            MADO3890
```

```
       END                                                              MAD03900
C     SUBROUTINE FOURT                                                  MAD03910
C                                                                       MAD03920
C     PURPOSE                                                           MAD03930
C                                                                       MAD03940
C     SUBROUTINE FOURT COMPUTES THE FORWARD AND INVERSE                 MAD03950
C     COOLEY-TUKEY FAST FOURIER TRANSFORM OF THE CONTENTS OF THE        MAD03960
C     ARRAY DATA.  FOR DATA A SINGLY-DIMENSIONED ARRAY OF LENGTH        MAD03970
C     L, THE JTH COMPONENT OF THE TRANSFORM IS GIVEN BY                 MAD03980
C        SUM(DATA(K)*W**(K-1)*(J-1))                                    MAD03990
C     WHERE THE SUM IS TAKEN OVER K, 1 .LE. K .LE. L, AND               MAD04000
C        W=EXP(ISIGN*2*PI*SQRT(-1)/L)                                   MAD04010
C                                                                       MAD04020
C     THE VALUE OF ISIGN DEPENDS UPON WHETHER A FORWARD OR INVERSE      MAD04030
C     TRANSFORM IS TO BE PERFORMED.  FOURT MAY ALSO BE USED ON A        MAD04040
C     MULTI-DIMENSIONAL ARRAY, IN WHICH CASE A FOURIER TRANSFORM IS     MAD04050
C     PERFORMED ALONG EACH DIMENSION IN TURN.                           MAD04060
C                                                                       MAD04070
C     CALLING SEQUENCE                                                  MAD04080
C                                                                       MAD04090
C     CALL FOURT(DATA,NN,NDIM,ISIGN,IFORM,WORK)                         MAD04100
C                                                                       MAD04110
C     DESCRIPTION OF ARGUMENTS                                          MAD04120
C                                                                       MAD04130
C     DATA  COMPLEX*8 MULTI-DIMENSIONAL ARRAY CONTAINING THE DATA TO    MAD04140
C           BE TRANSFORMED.  ON OUTPUT DATA CONTAINS THE TRANSFORM.     MAD04150
C           NORMAL FORTRAN ORDERING IS EXPECTED, THE FIRST SUBSCRIPT    MAD04160
C           CHANGING THE FASTEST.                                       MAD04170
C                                                                       MAD04180
C     NN    INTEGER*4 ARRAY CONTAINING THE DIMENSIONS OF THE ARRAY      MAD04190
C           DATA.                                                       MAD04200
C                                                                       MAD04210
C     NDIM  NUMBER OF DIMENSIONS OF THE ARRAY DATA = NUMBER OF ELE-     MAD04220
C           MENTS IN THE ARRAY NN.                                      MAD04230
C                                                                       MAD04240
C     ISIGN INTEGER INDICATING WHETHER FORWARD OR INVERSE TRANSFORM     MAD04250
C           IS TO BE PERFORMED.                                         MAD04260
C             ISIGN=-1 FOR FORWARD TRANSFORM                            MAD04270
C             ISIGN=1 FOR INVERSE TRANSFORM.                            MAD04280
C           NOTE:  THESE DEFINITIONS ARE NOT STANDARDIZED.  IN PAR-     MAD04290
C                  TICULAR, THE DEFINITIONS OF FORWARD AND INVERSE      MAD04300
C                  TRANSFORM ARE REVERSED IN THE IMSL FFT ROUTINES.     MAD04310
C                                                                       MAD04320
C     IFORM AN INTEGER INDICATING WHETHER OR NOT DATA CONTAINS ONLY     MAD04330
C           PURELY REAL VALUES.                                         MAD04340
C             IFORM=0 IF DATA IS PURELY REAL                            MAD04350
C             IFORM=1 OTHERWISE.                                        MAD04360
C           IF IFORM IS SET TO 0, ALL THE IMAGINARY PARTS OF THE ELE-   MAD04370
```

```
C           MENTS IN DATA MUST BE SET TO 0.0.                           MAD04380
C                                                                       MAD04390
C     WORK  A 1-DIMENSIONAL REAL*4 ARRAY USED FOR WORKING STORAGE.      MAD04400
C           ITS LENGTH SHOULD BE TWICE THE LARGEST ARRAY CIMENSICN      MAD04410
C           NN(I), I=1,2,...NDIM, WHICH IS NOT A POWER OF TWO.  IN      MAD04420
C           PARTICULAR, IF ALL NN(I) ARE POWERS OF TWO, NC WORK SPACE   MAD04430
C           IS NEEDED AND WORK MAY BE REPLACED BY ZERO IN THE CALLING   MAD04440
C           SEQUENCE.                                                   MAD04450
C                                                                       MAD04460
C     REMARKS                                                           MAD04470
C                                                                       MAD04480
C     IF AN INVERSE TRANSFORM (ISIGN=+1) IS PERFCRMED UPON AN ARRAY     MAD04490
C     OF TRANSFORMED (ISIGN=-1) DATA, THE ORIGINAL DATA WILL REAP-      MAD04500
C     PEAR, MULTIPLIED BY NN(1)*NN(2)*...*NN(NDIM).                     MAD04510
C                                                                       MAD04520
C     FOR A MULTI-DIMENSIONAL ARRAY THE (J1,J2,...,JNDIM)               MAD04530
C     COMPONENT OF THE TRANSFORM IS GIVEN BY                            MAD04540
C        SUM(DATA(I1,I2,...INDIM)*W1**((I1-1)*(J1-1))*                  MAD04550
C        W2**((I2-1)*(J2-1)*...*WNDIM**((INDIM-1)*(JNDIM-1))            MAD04560
C     HERE THE SUM RANGES OVER ALL PCSSIBLE VALUES OF THE I'S           MAD04570
C     AND W1=EXP(ISIGN*2*PI*SQRT(-1)/NN(1)), ETC.                       MAD04580
C                                                                       MAD04590
C     THE ARRAY OF INPUT DATA MUST BE IN COMPLEX FCRMAT.                MAD04600
C     HOWEVER, IS ALL IMAGINARY PARTS ARE ZERO (I.E., THE DATA          MAD04610
C     ARE DISGUISED REAL) RUNNING TIME IS CUT UP TC FORTY PER-          MAD04620
C     CENT.  (FOR FASTEST TRANSFORM OF REAL DATA, NN(1) SHCULD BE E-    MAD04630
C     VEN.)  THE TRANSFORM VALUES ARE ALWAYS COMPLEX AND ARE RETURNED   MAD04640
C     IN THE ORIGINAL ARRAY OF DATA, REPLACING THE INPUT CATA.  THE     MAD04650
C     LENGTH OF EACH DIMENSION OF THE DATA ARRAY MAY BE ANY INTEGER.    MAD04660
C     THE PROGRAM RUNS FASTER ON COMPOSITE INTEGERS THAN CN PRIMES,     MAD04670
C     AND IS PARTICULARLY FAST ON NUMBERS RICH IN FACTORS CF TWO.       MAD04680
C                                                                       MAD04690
C     TIMING IS IN FACT GIVEN BY THE FOLLOWING FORMULA.  LET NTOT BE    MAD04700
C     THE TOTAL NUMBER OF POINTS (REAL CR COMPLEX) IN THE DATA ARRAY,   MAD04710
C     THAT IS, NTCT=NN(1)*NN(2)*...  DECOMPOSE NTOT INTO ITS PRIME      MAD04720
C     FACTORS, SUCH AS 2**K2 * 3**K3 * 5**K5 * ...  LET SUM2 BE THE     MAD04730
C     SUM OF THE FACTORS OF TWO IN NTOT, THAT IS, SUM2 = 2*K2.  LET     MAD04740
C     SUMF BE THE SUM OF ALL CTHER FACTCRS OF NTOT, THAT IS, SUMF =     MAD04750
C     3*K3*5*K5*..  THE TIME TAKEN BY A MULTIDIMENSIONAL TRANSFCRM CN   MAD04760
C     THESE NTOT DATA IS T = TO + NTOT*(T1+T2*SUM2+T3*SUMF).  ON THE    MAD04770
C     CDC 3300 (FLOATING POINT ADD TIME = SIX MICROSECONDS), T = 3000+  MAD04780
C     NTOT*(600+40*SUM2+175*SUMF) MICROSECONDS ON CCMPLEX DATA.         MAD04790
C                                                                       MAD04800
C     THE SAVINGS OFFERED BY THIS PROGRAM CAN BE DRAMATIC.  A ONE-DI-   MAD04810
C     MENSIONAL ARRAY 4000 IN LENGTH WILL BE TRANSFORMED IN 4000*(600+  MAD04820
C     40*(2+2+2+2+2)+175*(5+5+5)) = 14.5 SECONDS VERSUS ABOUT 4000*     MAD04830
C     4000*175 = 2800 SECONDS FOR THE STRAIGHTFORWARD TECHNIQUE.        MAD04840
C                                                                       MAD04850
```

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C     THE FAST FOURIER TRANSFORM PLACES THREE RESTRICTIONS UPON THE     MAD04860
C     DATA.                                                             MAD04870
C     1.  THE NUMBER OF INPUT DATA AND THE NUMBER OF TRANSFORM VALUES   MAD04880
C         MUST BE THE SAME.                                             MAD04890
C     2.  BOTH THE INPUT DATA AND THE TRANSFORM VALUES MUST REPRESENT   MAD04900
C         EQUISPACED POINTS IN THEIR RESPECTIVE DOMAINS OF TIME AND     MAD04910
C         FREQUENCY.  CALLING THESE SPACINGS DELTAT AND DELTAF, IT      MAD04920
C         MUST BE TRUE THAT DELTAF=2*PI/(NN(I)*DELTAT).  OF COURSE,     MAD04930
C         DELTAT NEED NOT BE THE SAME FOR EVERY DIMENSION.              MAD04940
C     3.  CONCEPTUALLY AT LEAST, THE INPUT DATA AND THE TRANSFORM OUT-  MAD04950
C         PUT REPRESENT SINGLE CYCLES OF PERIODIC FUNCTIONS.            MAD04960
C                                                                       MAD04970
C     THERE ARE NO ERROR MESSAGES OR ERROR HALTS IN THIS PROGRAM.  THE  MAD04980
C     PROGRAM RETURNS IMMEDIATELY IF NDIM OR ANY NN(I) IS LESS THAN     MAD04990
C     ONE.                                                              MAD05000
C                                                                       MAD05010
C     FOR MOST APPLICATIONS FOURT, IF COMPILED UNDER FORTRAN H, IS      MAD05020
C     COMPARABLE IN SPEED AND ACCURACY TO THE IMSL FFT SUBROUTINES.     MAD05030
C     WITH CERTAIN PATHOLOGICALLY ILL-CONDITIONED DATA THE              MAD05040
C     ACCURACY OF FOURT MAY BE SERIOUSLY DEGRADED, BUT THE              MAD05050
C     SAME CAN PROBABLY BE SAID OF ANY EXTANT FFT ROUTINE.              MAD05060
C     WORK SPACE REQUIRED BY FOURT MAY BE GREATER OR LESS THAN THAT     MAD05070
C     REQUIRED BY THE IMSL ROUTINES, DEPENDING UPON THE APPLICATION.    MAD05080
C     FOURT IS MORE FLEXIBLE AND IN GENERAL EASIER TO USE THAN THE      MAD05090
C     IMSL ROUTINES.  FOURT ALONE PROVIDES THE CAPABILITY OF TRANS-     MAD05100
C     FORMING A MULTI-DIMENSIONAL ARRAY WITH A SINGLE CALL.             MAD05110
C                                                                       MAD05120
C     THIS IS THE FASTEST AND MOST VERSATILE VERSION OF THE FFT KNOWN   MAD05130
C     TO THE AUTHOR.  A PROGRAM CALLED FOUR2 IS AVAILABLE THAT ALSO     MAD05140
C     PERFORMS THE FAST FOURIER TRANSFORM AND IS WRITTEN IN USASI BA-   MAD05150
C     SIC FORTRAN.  IT IS ABOUT ONE THIRD AS LONG AND RESTRICTS THE     MAD05160
C     DIMENSIONS OF THE INPUT ARRAY (WHICH MUST BE COMPLEX) TO BE       MAD05170
C     POWERS OF TWO.  ANOTHER PROGRAM, CALLED FOUR1, IS ONE TENTH AS    MAD05180
C     LONG AND RUNS TWO THIRDS AS FAST ON A ONE-DIMENSIONAL COMPLEX     MAD05190
C     ARRAY WHOSE LENGTH IS A POWER OF TWO.                             MAD05200
C                                                                       MAD05210
C     REFERENCE--                                                       MAD05220
C     IEEE AUDIO TRANSACTIONS (JUNE 1967), SPECIAL ISSUE ON THE FFT.    MAD05230
C                                                                       MAD05240
C     EXAMPLE 1.  THREE-DIMENSIONAL FORWARD FOURIER TRANSFORM OF A      MAD05250
C     COMPLEX ARRAY DIMENSIONED 32 BY 25 BY 13 IN FORTRAN IV.           MAD05260
C     DIMENSION DATA(32,25,13),WORK(50),NN(3)                           MAD05270
C     COMPLEX DATA                                                      MAD05280
C     DATA NN/32,25,13/                                                 MAD05290
C     DO 1 I=1,32                                                       MAD05300
C     DO 1 J=1,25                                                       MAD05310
C     DO 1 K=1,13                                                       MAD05320
C   1 DATA(I,J,K)=COMPLEX VALUE                                         MAD05330
```

```
C     CALL FOURT(DATA,NN,3,-1,1,WORK)                                   MAD05340
C                                                                       MAD05350
C     EXAMPLE 2.  ONE-DIMENSIONAL FORWARD TRANSFORM OF A REAL ARRAY OF  MAD05360
C     LENGTH 64 IN FORTRAN II                                           MAD05370
C     DIMENSION DATA(2,64)                                              MAD05380
C     DO 2 I=1,64                                                       MAD05390
C     DATA(1,I)=REAL PART                                               MAD05400
C   2 DATA(2,I)=0.                                                      MAD05410
C     CALL FOURT(DATA,64,1,-1,0,0)                                      MAD05420
C                                                                       MAD05430
C     PROGRAMMER                                                        MAD05440
C                                                                       MAD05450
C     PROGRAM BY NORMAN BRENNER FROM THE BASIC PROGRAM BY CHARLES       MAD05460
C     RADER,  JUNE 1967.  THE IDEA FOR THE DIGIT REVERSAL WAS           MAD05470
C     SUGGESTED BY RALPH ALTER.                                         MAD05480
C     DOCUMENTATION REVISED BY JOANNE BOGART, AUGUST 1979, NPS.         MAD05490
C                                                                       MAD05500
      SUBROUTINE FOURT(DATA,NN,NDIM,ISIGN,IFORM,WORK)                   MAD05510
      DIMENSION DATA(1),NN(1),IFACT(32),WORK(1)                         MAD05520
      DATA TWOPI/6.2831853071796/,RTHLF/0.70710678118655/               MAD05530
      IF(NDIM-1)920,1,1                                                 MAD05540
 1    NTOT=2                                                            MAD05550
      DO 2 IDIM=1,NDIM                                                  MAD05560
      IF(NN(IDIM))920,920,2                                             MAD05570
 2    NTOT=NTOT*NN(IDIM)                                                MAD05580
C                                                                       MAD05590
C     MAIN LOOP FOR EACH DIMENSION                                      MAD05600
C                                                                       MAD05610
      NP1=2                                                             MAD05620
      DO 910 IDIM=1,NDIM                                                MAD05630
      N=NN(IDIM)                                                        MAD05640
      NP2=NP1*N                                                         MAD05650
      IF(N-1)920,900,5                                                  MAD05660
C                                                                       MAD05670
C     IS N A POWER OF TWO AND IF NOT, WHAT ARE ITS FACTORS              MAD05680
C                                                                       MAD05690
 5    M=N                                                               MAD05700
      NTWO=NP1                                                          MAD05710
      IF=1                                                              MAD05720
      IDIV=2                                                            MAD05730
 10   IQUOT=M/IDIV                                                      MAD05740
      IREM=M-IDIV*IQUOT                                                 MAD05750
      IF(IQUOT-IDIV)50,11,11                                            MAD05760
 11   IF(IREM)20,12,20                                                  MAD05770
 12   NTWO=NTWO+NTWO                                                    MAD05780
      IFACT(IF)=IDIV                                                    MAD05790
      IF=IF+1                                                           MAD05800
      M=IQUOT                                                           MAD05810
```

```
      GO TO 10                                                          MAD05820
   20 IDIV=3                                                            MAD05830
      INON2=IF                                                          MAD05840
   30 IQUCT=M/IDIV                                                      MAD05850
      IREM=M-IDIV*IQUOT                                                 MAD05860
      IF(IQUOT-IDIV)60,31,31                                            MAD05870
   31 IF(IREM)40,32,40                                                  MAD05880
   32 IFACT(IF)=IDIV                                                    MAD05890
      IF=IF+1                                                           MAD05900
      M=IQUOT                                                           MAD05910
      GO TO 30                                                          MAD05920
   40 IDIV=IDIV+2                                                       MAD05930
      GC TO 30                                                          MAD05940
   50 INON2=IF                                                          MAD05950
      IF(IREM)60,51,60                                                  MAD05960
   51 NTWO=NTWO+NTWO                                                    MAD05970
      GO TO 70                                                          MAD05980
   60 IFACT(IF)=M                                                       MAD05990
C                                                                       MAD06000
C     SEPARATE FOUR CASES--                                             MAD06010
C        1. COMPLEX TRANSFORM OR REAL TRANSFORM FOR THE 4TH, 9TH, ETC.  MAD06020
C           DIMENSIONS.                                                 MAD06030
C        2. REAL TRANSFORM FOR THE 2ND CR 3RD DIMENSICN.  METHCD--      MAD06040
C           TRANSFORM HALF THE DATA, SUPPLYING THE OTHER HALF BY CON-   MAD06050
C           JUGATE SYMMETRY.                                            MAD06060
C        3. REAL TRANSFORM FOR THE 1ST DIMENSION, N ODD.  METHOD--      MAD06070
C           SET THE IMAGINARY PARTS TO ZERO.                            MAD06080
C        4. REAL TRANSFORM FOR THE 1ST DIMENSION, N EVEN.  METHOD--     MAD06090
C           TRANSFORM A COMPLEX ARRAY OF LENGTH N/2 WHOSE REAL PARTS    MAD06100
C           ARE THE EVEN NUMBERED REAL VALUES AND WHOSE IMAGINARY       MAD06110
C           PARTS ARE THE ODD NUMBERED REAL VALUES.  SEPARATE AND SUP-  MAD06120
C           PLY THE SECCND HALF BY CONJUGATE SYMMETRY.                  MAD06130
C                                                                       MAD06140
   70 ICASE=1                                                           MAD06150
      IFMIN=1                                                           MAD06160
      I1RNG=NP1                                                         MAD06170
      IF(IDIM-4)71,100,100                                              MAD06180
   71 IF(IFORM)72,72,100                                                MAD06190
   72 ICASE=2                                                           MAD06200
      I1RNG=NP0*(1+NPREV/2)                                             MAD06210
      IF(IDIM-1)73,73,100                                               MAD06220
   73 ICASE=3                                                           MAD06230
      I1RNG=NP1                                                         MAD06240
      IF(NTWO-NP1)100,100,74                                            MAD06250
   74 ICASE=4                                                           MAD06260
      IFMIN=2                                                           MAD06270
      NTWO=NTWO/2                                                       MAD06280
      N=N/2                                                             MAD06290
```

```
      NP2=NP2/2                                                         MAD06300
      NTOT=NTOT/2                                                       MAD06310
      I=1                                                               MAD06320
      DO 80 J=1,NTOT                                                    MAD06330
      DATA(J)=DATA(I)                                                   MAD06340
 80   I=I+2                                                             MAD06350
C                                                                       MAD06360
C     SHUFFLE DATA BY BIT REVERSAL, SINCE N=2**K.  AS THE  SHUFFLING    MAD06370
C     CAN BE DONE BY SIMPLE INTERCHANGE, NO WORKING ARRAY IS NEEDED     MAD06380
C                                                                       MAD06390
 100  IF(NTWO-NP2)200,110,110                                           MAD06400
 110  NP2HF=NP2/2                                                       MAD06410
      J=1                                                               MAD06420
      DO 150 I2=1,NP2,NP1                                               MAD06430
      IF(J-I2)120,130,130                                               MAD06440
 120  I1MAX=I2+NP1-2                                                    MAD06450
      DO 125 I1=I2,I1MAX,2                                              MAD06460
      DO 125 I3=I1,NTOT,NP2                                             MAD06470
      J3=J+I3-I2                                                        MAD06480
      TEMPR=DATA(I3)                                                    MAD06490
      TEMPI=DATA(I3+1)                                                  MAD06500
      DATA(I3)=DATA(J3)                                                 MAD06510
      DATA(I3+1)=DATA(J3+1)                                             MAD06520
      DATA(J3)=TEMPR                                                    MAD06530
 125  DATA(J3+1)=TEMPI                                                  MAD06540
 130  M=NP2HF                                                           MAD06550
 140  IF(J-M)150,150,145                                                MAD06560
 145  J=J-M                                                             MAD06570
      M=M/2                                                             MAD06580
      IF(M-NP1)150,140,140                                              MAD06590
 150  J=J+M                                                             MAD06600
      GO TO 300                                                         MAD06610
C                                                                       MAD06620
C     SHUFFLE DATA BY DIGIT REVERSAL FOR GENERAL NO ARRAY IS NEEDED     MAD06630
C                                                                       MAD06640
 200  NWORK=2*N                                                         MAD06650
      DO 270 I1=1,NP1,2                                                 MAD06660
      DO 270 I3=I1,NTOT,NP2                                             MAD06670
      J=I3                                                              MAD06680
      DO 260 I=1,NWORK,2                                                MAD06690
      IF(ICASE-3)210,220,210                                            MAD06700
 210  WORK(I)=DATA(J)                                                   MAD06710
      WORK(I+1)=DATA(J+1)                                               MAD06720
      GO TO 230                                                         MAD06730
 220  WORK(I)=DATA(J)                                                   MAD06740
      WORK(I+1)=0.                                                      MAD06750
 230  IFP2=NP2                                                          MAD06760
      IF=IFMIN                                                          MAD06770
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  240 IFP1=IFP2/IFACT(IF)                                                MAD06780
      J=J+IFP1                                                           MAD06790
      IF(J-I3-IFP2)260,250,250                                           MAD06800
  250 J=J-IFP2                                                           MAD06810
      IFP2=IFP1                                                          MAD06820
      IF=IF+1                                                            MAD06830
      IF(IFP2-NP1)260,260,240                                            MAD06840
  260 CONTINUE                                                           MAD06850
      I2MAX=I3+NP2-NP1                                                   MAD06860
      I=1                                                                MAD06870
      DO 270 I2=I3,I2MAX,NP1                                             MAD06880
      DATA(I2)=WORK(I)                                                   MAD06890
      DATA(I2+1)=WORK(I+1)                                               MAD06900
  270 I=I+2                                                              MAD06910
C                                                                        MAD06920
C     MAIN LOOP FOR FACTORS OF TWO.  PERFORM FOURIER TRANSFORMS OF       MAD06930
C     LENGTH FOUR, WITH ONE OF LENGTH TWO IF NEEDED.  THE TWIDDLE FAC-   MAD06940
C     TOR W=EXP(ISIGN*2*PI*SQRT(-1)*M/(4*MMAX)).  CHECK FOR W=ISIGN*     MAD06950
C     SQRT(-1)                                                           MAD06960
C                                                                        MAD06970
  300 IF(NTWO-NP1)600,600,305                                            MAD06980
  305 NP1TW=NP1+NP1                                                      MAD06990
      IPAR=NTWO/NP1                                                      MAD07000
  310 IF(IPAR-2)350,330,320                                              MAD07010
  320 IPAR=IPAR/4                                                        MAD07020
      GO TO 310                                                          MAD07030
  330 DO 340 I1=1,I1RNG,2                                                MAD07040
      DO 340 K1=I1,NTOT,NP1TW                                            MAD07050
      K2=K1+NP1                                                          MAD07060
      TEMPR=DATA(K2)                                                     MAD07070
      TEMPI=DATA(K2+1)                                                   MAD07080
      DATA(K2)=DATA(K1)-TEMPR                                            MAD07090
      DATA(K2+1)=DATA(K1+1)-TEMPI                                        MAD07100
      DATA(K1)=DATA(K1)+TEMPR                                            MAD07110
  340 DATA(K1+1)=DATA(K1+1)+TEMPI                                        MAD07120
  350 MMAX=NP1                                                           MAD07130
  360 IF(MMAX-NTWO/2)370,600,600                                         MAD07140
  370 LMAX=MAX0(NP1TW,MMAX/2)                                            MAD07150
      DO 570 L=NP1,LMAX,NP1TW                                            MAD07160
      M=L                                                                MAD07170
      IF(MMAX-NP1)420,420,380                                            MAD07180
  380 THETA=-TWOPI*FLOAT(L)/FLOAT(4*MMAX)                                MAD07190
      IF(ISIGN)400,390,390                                               MAD07200
  390 THETA=-THETA                                                       MAD07210
  400 WR=COS(THETA)                                                      MAD07220
      WI=SIN(THETA)                                                      MAD07230
  410 W2R=WR*WR-WI*WI                                                    MAD07240
      W2I=2.*WR*WI                                                       MAD07250
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      W3R=W2R*WR-W2I*WI                                                 MAD07260
      W3I=W2R*WI+W2I*WR                                                 MAD07270
420   DO 530 I1=1,I1RNG,2                                               MAD07280
      KMIN=I1+IPAR*M                                                    MAD07290
      IF(MMAX-NP1)430,430,440                                           MAD07300
430   KMIN=I1                                                           MAD07310
440   KDIF=IPAR*MMAX                                                    MAD07320
450   KSTEP=4*KDIF                                                      MAD07330
      IF(KSTEP-NTWO)460,460,530                                         MAD07340
460   DO 520 K1=KMIN,NTOT,KSTEP                                         MAD07350
      K2=K1+KDIF                                                        MAD07360
      K3=K2+KDIF                                                        MAD07370
      K4=K3+KDIF                                                        MAD07380
      IF(MMAX-NP1)470,470,480                                           MAD07390
470   U1R=DATA(K1)+DATA(K2)                                             MAD07400
      U1I=DATA(K1+1)+DATA(K2+1)                                         MAD07410
      U2R=DATA(K3)+DATA(K4)                                             MAD07420
      U2I=DATA(K3+1)+DATA(K4+1)                                         MAD07430
      U3R=DATA(K1)-DATA(K2)                                             MAD07440
      U3I=DATA(K1+1)-DATA(K2+1)                                         MAD07450
      IF(ISIGN)471,472,472                                              MAD07460
471   U4R=DATA(K3+1)-DATA(K4+1)                                         MAD07470
      U4I=DATA(K4)-DATA(K3)                                             MAD07480
      GO TO 510                                                         MAD07490
472   U4R=DATA(K4+1)-DATA(K3+1)                                         MAD07500
      U4I=DATA(K3)-DATA(K4)                                             MAD07510
      GO TO 510                                                         MAD07520
480   T2R=W2R*DATA(K2)-W2I*DATA(K2+1)                                   MAD07530
      T2I=W2R*DATA(K2+1)+W2I*DATA(K2)                                   MAD07540
      T3R=WR*DATA(K3)-WI*DATA(K3+1)                                     MAD07550
      T3I=WR*DATA(K3+1)+WI*DATA(K3)                                     MAD07560
      T4R=W3R*DATA(K4)-W3I*DATA(K4+1)                                   MAD07570
      T4I=W3R*DATA(K4+1)+W3I*DATA(K4)                                   MAD07580
      U1R=DATA(K1)+T2R                                                  MAD07590
      U1I=DATA(K1+1)+T2I                                                MAD07600
      U2R=T3R+T4R                                                       MAD07610
      U2I=T3I+T4I                                                       MAD07620
      U3R=DATA(K1)-T2R                                                  MAD07630
      U3I=DATA(K1+1)-T2I                                                MAD07640
      IF(ISIGN)490,500,500                                              MAD07650
490   U4R=T3I-T4I                                                       MAD07660
      U4I=T4R-T3R                                                       MAD07670
      GO TO 510                                                         MAD07680
500   U4R=T4I-T3I                                                       MAD07690
      U4I=T3R-T4R                                                       MAD07700
510   DATA(K1)=U1R+U2R                                                  MAD07710
      DATA(K1+1)=U1I+U2I                                                MAD07720
      DATA(K2)=U3R+U4R                                                  MAD07730
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      DATA(K2+1)=U3I+U4I                                                MAD07740
      DATA(K3)=U1R-U2R                                                  MAD07750
      DATA(K3+1)=U1I-U2I                                                MAD07760
      DATA(K4)=U3R-U4R                                                  MAD07770
  520 DATA(K4+1)=U3I-U4I                                                MAD07780
      KDIF=KSTEP                                                        MAD07790
      KMIN=4*(KMIN-I1)+I1                                               MAD07800
      GO TO 450                                                         MAD07810
  530 CONTINUE                                                          MAD07820
      M=M+LMAX                                                          MAD07830
      IF(M-MMAX)540,540,570                                             MAD07840
  540 IF(ISIGN)550,560,560                                              MAD07850
  550 TEMPR=WR                                                          MAD07860
      WR=(WR+WI)*RTHLF                                                  MAD07870
      WI=(WI-TEMPR)*RTHLF                                               MAD07880
      GO TO 410                                                         MAD07890
  560 TEMPR=WR                                                          MAD07900
      WR=(WR-WI)*RTHLF                                                  MAD07910
      WI=(TEMPR+WI)*RTHLF                                               MAD07920
      GO TO 410                                                         MAD07930
  570 CONTINUE                                                          MAD07940
      IPAR=3-IPAR                                                       MAD07950
      MMAX=MMAX+MMAX                                                    MAD07960
      GO TO 360                                                         MAD07970
C                                                                       MAD07980
C     MAIN LOOP FOR FACTORS NOT EQUAL TO TWO.  APPLY THE TWIDDLE FAC-   MAD07990
C     TOR W=EXP(ISIGN*2*PI*SQRT(-1)*(J1-1)*(J2-J1)/(IFP1+IFP2)),        MAD08000
C     THEN PERFORM A FOURIER TRANSFORM OF LENGTH IFACT(IF), MAKING USE  MAD08010
C     OF CONJUGATE SYMMETRIES.                                          MAD08020
C                                                                       MAD08030
  600 IF(NTWO-NP2)605,700,700                                           MAD08040
  605 IFP1=NTWO                                                         MAD08050
      IF=INON2                                                          MAD08060
      NP1HF=NP1/2                                                       MAD08070
  610 IFP2=IFACT(IF)*IFP1                                               MAD08080
      J1MIN=NP1+1                                                       MAD08090
      IF(J1MIN-IFP1)615,615,640                                         MAD08100
  615 DO 635 J1=J1MIN,IFP1,NP1                                          MAD08110
      THETA=-TWOPI*FLOAT(J1-1)/FLOAT(IFP2)                              MAD08120
      IF(ISIGN)625,620,620                                              MAD08130
  620 THETA=-THETA                                                      MAD08140
  625 WSTPR=COS(THETA)                                                  MAD08150
      WSTPI=SIN(THETA)                                                  MAD08160
      WR=WSTPR                                                          MAD08170
      WI=WSTPI                                                          MAD08180
      J2MIN=J1+IFP1                                                     MAD08190
      J2MAX=J1+IFP2-IFP1                                                MAD08200
      DO 635 J2=J2MIN,J2MAX,IFP1                                        MAD08210
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      I1MAX=J2+I1RNG-2                                                  MAD08220
      DO 630  I1=J2,I1MAX,2                                             MAD08230
      DO 630  J3=I1,NTOT,IFP2                                           MAD08240
      TEMPR=DATA(J3)                                                    MAD08250
      DATA(J3)=DATA(J3)*WR-DATA(J3+1)*WI                                MAD08260
630   DATA(J3+1)=TEMPR*WI+DATA(J3+1)*WR                                 MAD08270
      TEMPR=WR                                                          MAD08280
      WR=WR*WSTPR-WI*WSTPI                                              MAD08290
635   WI=TEMPR*WSTPI+WI*WSTPR                                           MAD08300
640   THETA=-TWOPI/FLOAT(IFACT(IF))                                     MAD08310
      IF(ISIGN)650,645,645                                              MAD08320
645   THETA=-THETA                                                      MAD08330
650   WSTPR=COS(THETA)                                                  MAD08340
      WSTPI=SIN(THETA)                                                  MAD08350
      J2RNG=IFP1*(1+IFACT(IF)/2)                                        MAD08360
      DO 695  I1=1,I1RNG,2                                              MAD08370
      DO 695  I3=I1,NTOT,NP2                                            MAD08380
      J2MAX=I3+J2RNG-IFP1                                               MAD08390
      DO 690  J2=I3,J2MAX,IFP1                                          MAD08400
      J1MAX=J2+IFP1-NP1                                                 MAD08410
      DO 680  J1=J2,J1MAX,NP1                                           MAD08420
      J3MAX=J1+NP2-IFP2                                                 MAD08430
      DO 680  J3=J1,J3MAX,IFP2                                          MAD08440
      JMIN=J3-J2+I3                                                     MAD08450
      JMAX=JMIN+IFP2-IFP1                                               MAD08460
      I=1+(J3-I3)/NP1HF                                                 MAD08470
      IF(J2-I3)655,655,665                                              MAD08480
655   SUMR=0.                                                           MAD08490
      SUMI=0.                                                           MAD08500
      DO 660  J=JMIN,JMAX,IFP1                                          MAD08510
      SUMR=SUMR+DATA(J)                                                 MAD08520
660   SUMI=SUMI+DATA(J+1)                                               MAD08530
      WORK(I)=SUMR                                                      MAD08540
      WORK(I+1)=SUMI                                                    MAD08550
      GO TO 680                                                         MAD08560
665   ICONJ=1+(IFP2-2*J2+I3+J3)/NP1HF                                   MAD08570
      J=JMAX                                                            MAD08580
      SUMR=DATA(J)                                                      MAD08590
      SUMI=DATA(J+1)                                                    MAD08600
      OLDSR=0.                                                          MAD08610
      OLDSI=0.                                                          MAD08620
      J=J-IFP1                                                          MAD08630
670   TEMPR=SUMR                                                        MAD08640
      SUMR=TWOWR*SUMR-OLDSR+DATA(J)                                     MAD08650
      TEMPI=SUMI                                                        MAD08660
      SUMI=TWOWR*SUMI-OLDSI+DATA(J+1)                                   MAD08670
      OLDSR=TEMPR                                                       MAD08680
      OLDSI=TEMPI                                                       MAD08690
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      J=J-IFP1                                                          MAD08700
      IF(J-JMIN)675,675,670                                             MAD08710
  675 TEMPR=WR*SUMR-OLDSR+DATA(J)                                       MAD08720
      TEMPI=WI*SUMI                                                     MAD08730
      WORK(I)=TEMPR-TEMPI                                               MAD08740
      WORK(ICONJ)=TEMPR+TEMPI                                           MAD08750
      TEMPR=WR*SUMI-OLDSI+DATA(J+1)                                     MAD08760
      TEMPI=WI*SUMR                                                     MAD08770
      WORK(I+1)=TEMPR+TEMPI                                             MAD08780
      WORK(ICONJ+1)=TEMPR-TEMPI                                         MAD08790
  680 CONTINUE                                                          MAD08800
      IF(J2-I3)685,685,686                                              MAD08810
  685 WR=WSTPR                                                          MAD08820
      WI=WSTPI                                                          MAD08830
      GO TO 690                                                         MAD08840
  686 TEMPR=WR                                                          MAD08850
      WR=WR*WSTPR-WI*WSTPI                                              MAD08860
      WI=TEMPR*WSTPI+WI*WSTPR                                           MAD08870
  690 TWOWR=WR+WR                                                       MAD08880
      I=1                                                               MAD08890
      I2MAX=I3+NP2-NP1                                                  MAD08900
      DO 695 I2=I3,I2MAX,NP1                                            MAD08910
      DATA(I2)=WORK(I)                                                  MAD08920
      DATA(I2+1)=WORK(I+1)                                              MAD08930
  695 I=I+2                                                             MAD08940
      IF=IF+1                                                           MAD08950
      IFP1=IFP2                                                         MAD08960
      IF(IFP1-NP2)610,700,700                                           MAD08970
C                                                                       MAD08980
C     COMPLETE A REAL TRANSFORM IN THE 1ST DIMENSION, N EVEN, BY CON-   MAD08990
C     JUGATE SYMMETRIES.                                                MAD09000
C                                                                       MAD09010
  700 GO TO (900,800,900,701),ICASE                                     MAD09020
  701 NHALF=N                                                           MAD09030
      N=N+N                                                             MAD09040
      THETA=-TWOPI/FLOAT(N)                                             MAD09050
      IF(ISIGN)703,702,702                                              MAD09060
  702 THETA=-THETA                                                      MAD09070
  703 WSTPR=COS(THETA)                                                  MAD09080
      WSTPI=SIN(THETA)                                                  MAD09090
      WR=WSTPR                                                          MAD09100
      WI=WSTPI                                                          MAD09110
      IMIN=3                                                            MAD09120
      JMIN=2*NHALF-1                                                    MAD09130
      GO TO 725                                                         MAD09140
  710 J=JMIN                                                            MAD09150
      DO 720 I=IMIN,NTOT,NP2                                            MAD09160
      SUMR=(DATA(I)+DATA(J))/2.                                         MAD09170
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      SUMI=(DATA(I+1)+DATA(J+1))/2.                                     MAD09180
      DIFR=(DATA(I)-DATA(J))/2.                                         MAD09190
      DIFI=(DATA(I+1)-DATA(J+1))/2.                                     MAD09200
      TEMPR=WR*SUMI+WI*DIFR                                             MAD09210
      TEMPI=WI*SUMI-WR*DIFR                                             MAD09220
      DATA(I)=SUMR+TEMPR                                                MAD09230
      DATA(I+1)=DIFI+TEMPI                                              MAD09240
      DATA(J)=SUMR-TEMPR                                                MAD09250
      DATA(J+1)=-DIFI+TEMPI                                             MAD09260
  720 J=J+NP2                                                           MAD09270
      IMIN=IMIN+2                                                       MAD09280
      JMIN=JMIN-2                                                       MAD09290
      TEMPR=WR                                                          MAD09300
      WR=WR*WSTPR-WI*WSTPI                                              MAD09310
      WI=TEMPR*WSTPI+WI*WSTPR                                           MAD09320
  725 IF(IMIN-JMIN)710,730,740                                          MAD09330
  730 IF(ISIGN)731,740,740                                              MAD09340
  731 DO 735 I=IMIN,NTOT,NP2                                            MAD09350
  735 DATA(I+1)=-DATA(I+1)                                              MAD09360
  740 NP2=NP2+NP2                                                       MAD09370
      NTOT=NTOT+NTOT                                                    MAD09380
      J=NTOT+1                                                          MAD09390
      IMAX=NTOT/2+1                                                     MAD09400
  745 IMIN=IMAX-2*NHALF                                                 MAD09410
      I=IMIN                                                            MAD09420
      GO TO 755                                                         MAD09430
  750 DATA(J)=DATA(I)                                                   MAD09440
      DATA(J+1)=-DATA(I+1)                                              MAD09450
  755 I=I+2                                                             MAD09460
      J=J-2                                                             MAD09470
      IF(I-IMAX)750,760,760                                             MAD09480
  760 DATA(J)=DATA(IMIN)-DATA(IMIN+1)                                   MAD09490
      DATA(J+1)=0.                                                      MAD09500
      IF(I-J)770,780,780                                                MAD09510
  765 DATA(J)=DATA(I)                                                   MAD09520
  770 I=I-2                                                             MAD09530
      J=J-2                                                             MAD09540
      IF(I-IMIN)775,775,765                                             MAD09550
  775 DATA(J)=DATA(IMIN)+DATA(IMIN+1)                                   MAD09560
      DATA(J+1)=0.                                                      MAD09570
      IMAX=IMIN                                                         MAD09580
      GO TO 745                                                         MAD09590
  780 DATA(1)=DATA(1)+DATA(2)                                           MAD09600
      DATA(2)=0.                                                        MAD09610
      GO TO 900                                                         MAD09620
C                                                                       MAD09630
C     COMPLETE A REAL TRANSFORM FOR THE 2ND OR 3RD DIMENSION BY         MAD09640
C     CONJUGATE SYMMETRIES.                                             MAD09650
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C                                                                       MAD09660
  800   IF(I1RNG-NP1)805,900,900                                        MAD09670
  805   DO 860 I3=1,NTOT,NP2                                            MAD09680
        I2MAX=I3+NP2-NP1                                                MAD09690
        DO 860 I2=I3,I2MAX,NP1                                          MAD09700
        IMIN=I2+I1RNG                                                   MAD09710
        IMAX=I2+NP1-2                                                   MAD09720
        JMAX=2*I3+NP1-IMIN                                              MAD09730
        IF(I2-I3)820,820,810                                            MAD09740
  810   JMAX=JMAX+NP2                                                   MAD09750
  820   IF(IDIM-2)850,850,830                                           MAD09760
  830   J=JMAX*NPO                                                      MAD09770
        DO 840 I=IMIN,IMAX,2                                            MAD09780
        DATA(I)=DATA(J)                                                 MAD09790
        DATA(I+1)=-DATA(J+1)                                            MAD09800
  840   J=J-2                                                           MAD09810
  850   J=JMAX                                                          MAD09820
        DO 860 I=IMIN,IMAX,NPO                                          MAD09830
        DATA(I)=DATA(J)                                                 MAD09840
        DATA(I+1)=-DATA(J+1)                                            MAD09850
  860   J=J-NPO                                                         MAD09860
C                                                                       MAD09870
C       END OF LOOP ON EACH DIMENSION                                   MAD09880
C                                                                       MAD09890
  900   NPO=NP1                                                         MAD09900
        NP1=NP2                                                         MAD09910
  910   NPREV=N                                                         MAD09920
  920   RETURN                                                          MAD09930
        END                                                             MAD09940
        SUBROUTINE CHBFT                                                MAD09950
C                                                                       MAD09960
C                                                                       MAD09970
C       PURPOSE:                                                        MAD09980
C           SUBROUTINE CHBFT  EVALUATES THE COEFFICIENTS OF AN MTH ORDER MAD09980
C           POLYNOMIAL P(X)=A(1)+A(2)*X+A(3)*X**2+...+A(M+1)X**M  SUCH  MAD09990
C           THAT THE MAXIMUM ERROR ABS(P(X(I))-Y(I)) IS A MINIMUM OVER  MAD10000
C           THE N (N.GT.M+1) SAMPLE POINTS X(I),Y(I), I=1,2,...,N.  THE MAD10010
C           X(I) MUST FORM A STRICTLY MONOTONIC SEQUENCE; I.E.,         MAD10020
C           X(1).LT.X(2).LT.X(3).LT....X(N). THIS SUBROUTINE IS A       MAD10030
C           CONVERSION FROM ALGOL TO FORTRAN OF ALGORITHM 318, CHEBYSCHEV MAD10040
C           CURVE-FIT FROM"COMMUNICATIONS OF THE ACM"VOL.10,NUMBER 12,  MAD10050
C           DECEMBER,1967. THE AUTHOR OF THE ALGOL VERSION WAS          MAD10060
C           J. BOOTHROYD FROM THE UNIVERSITY OF TASMANIA.               MAD10070
C                                                                       MAD10080
C       USAGE:                                                          MAD10090
C           CALL CHBFT (X,Y,N,A,M,RX,RH,R)                              MAD10100
C                                                                       MAD10110
C           DESCRIPTION OF PARAMETERS:                                  MAD10120
C           X     -ARRAY OF ABSCISSAE DIMENSIONED REAL*4 X(N)           MAD10130
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C          Y      -ARRAY OF CRDINATES DIMENSIONED REAL*4 Y(N)                 MAD10140
C          N      -NUMBER CF SAMPLE POINTS  (INTEGER)                         MAD10150
C          A      -ARRAY OF THE OUTPUTTED POLYNOMIAL CCEFFICIENTS             MAD10160
C                  DIMENSICNED AT LEAST A(M+2) (REAL*4)                       MAD10170
C          M      -ORDER OF DESIRED APPROXIMATING PCLYNOMIAL                  MAD10180
C          RX     -WORK ARRAY DIMENSIONED AT LEAST REAL*4 RX(M+2)             MAD10190
C          RH     -WCRK ARRAY DIMENSIONED AT LEAST REAL*4 RH(M+2)             MAD10200
C          R      -INTEGER WORK ARRAY DIMENSIONED AT LEAST R(M+2)             MAD10210
C                                                                             MAD10220
C     REMARKS:                                                                MAD10230
C          THE POLYNOMIAL P(X) IS A BEST-FIT PCLYNCMIAL IN THE CHEBYSCHEVMAD10240
C          SENSE AS DESCRIBED BY STIEFEL(NUMERICAL METHODS OF                 MAD10250
C          TCHEBYCHEFF APPROXIMATION), IN LANGER(ED.),"ON NUMERICAL           MAD10260
C          APPROXIMATION",U.OF WISCONSIN PRESS, 1959, PP. 217-232.           MAD10270
C          STIEFEL (P.221) SHOWS THAT THE PROCEDURE MUST TERMINATE AFTER MAD10280
C          A FINITE NUMBER OF STEPS. AT EXIT THE ABSCLUTE VALUE CF            MAD10290
C          A(M+1) YIELDS THE FINAL REFERENCE DEVIATION. NEGATIVE A(M+1)      MAD10300
C          INDICATES THAT THE PROCEDURE HAS BEEN TERMINATEC FOLLOWING         MAD10310
C          THE DETECTION OF CYCLING.                                          MAD10320
C                                                                             MAD10330
C     NOTE:  DIVIDED DIFFERENCES AND NEWTCN'S INTERPOLATING FORMULA IS        MAD10340
C          USED FOR COMPUTING THE POLYNOMIAL COEFFICIENTS.                    MAD10350
C                                                                             MAD10360
C                                                                             MAD10370
      SUBROUTINE CHBFT(X,Y,N,A,M,RX,RH,R)                                     MAD10380
      REAL*4 NEXTHI                                                           MAD10390
      INTEGER RI,RJ,R(1)                                                      MAD10400
      DIMENSION X(1),Y(1),A(1),RX(1),RH(1)                                    MAD10410
      MPLUS1=M+1                                                              MAD10420
      MPLUS2=M+2                                                              MAD10430
      PREVH=0.0                                                               MAD10440
C     DETERMINE INDEX VECTOR FOR INITIAL REFERENCE SET                        MAD10450
      R(1)=1                                                                  MAD10460
      R(MPLUS2)=N                                                             MAD10470
      D=(N-1)/MPLUS1                                                          MAD10480
      H=D                                                                     MAD10490
      DO 1 I=2,MPLUS1                                                         MAD10500
      R(I)=H+1.0                                                              MAD10510
    1 H=H+D                                                                   MAD10520
    2 H=-1.0                                                                  MAD10530
C     SELECT M+2 REFERENCE PAIRS AND SET ALTERNATIVE DEVIATION VECTCR         MAD10540
      DO 3 I=1,MPLUS2                                                         MAD10550
      RI=R(I)                                                                 MAD10560
      RX(I)=X(RI)                                                             MAD10570
      A(I)=Y(RI)                                                              MAD10580
      H=-H                                                                    MAD10590
    3 RH(I)=H                                                                 MAD10600
C     COMPUTE M+1 LEADING DIVIDED DIFFERENCES                                 MAD10610
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      DO 4 J=1,MPLUS1                                                   MAD10620
      I1=MPLUS2                                                         MAD10630
      AI1=A(I1)                                                         MAD10640
      RHI1=RH(I1)                                                       MAD10650
      I=MPLUS1                                                          MAD10660
    5 DENOM=RX(I1)-RX(I-J+1)                                            MAD10670
      AI=A(I)                                                           MAD10680
      RHI=RH(I)                                                         MAD10690
      A(I1)=(AI1-AI)/DENOM                                              MAD10700
      RH(I1)=(RHI1-RHI)/DENOM                                           MAD10710
      I1=I                                                              MAD10720
      AI1=AI                                                            MAD10730
      RHI1=RHI                                                          MAD10740
      I=I-1                                                             MAD10750
      IF(I-J) 4,5,5                                                     MAD10760
    4 CONTINUE                                                          MAD10770
C     EQUATE (M+1) THE DIFFERENCE TO ZERO TO DETERMINE H                MAD10780
      H=-A(MPLUS2)/RH(MPLUS2)                                           MAD10790
C     WITH H KNOWN, COMBINE THE FUNCTION AND DEVIATION DIFFERENCES      MAD10800
      DO 6 I=1,MPLUS2                                                   MAD10810
    6 A(I)=A(I)+RH(I)*H                                                 MAD10820
C     COMPUTE POLYNOMIAL COEFFICIENTS                                   MAD10830
      J=M                                                               MAD10840
    7 XJ=RX(J)                                                          MAD10850
      I=J                                                               MAD10860
      AI=A(I)                                                           MAD10870
      JPLUS1=J+1                                                        MAD10880
      DO 8 I1=JPLUS1,MPLUS1                                             MAD10890
      AI1=A(I1)                                                         MAD10900
      A(I)=AI-XJ*AI1                                                    MAD10910
      AI=AI1                                                            MAD10920
    8 I=I1                                                              MAD10930
      J=J-1                                                             MAD10940
      IF(J-1) 9,7,7                                                     MAD10950
    9 CONTINUE                                                          MAD10960
C     IF THE REFERENCE DEVIATION IS NOT INCREASING MONOTONICALLY        MAD10970
C     THEN EXIT                                                         MAD10980
      HMAX=ABS(H)                                                       MAD10990
      IF(HMAX.GT.PREVH) GO TO 29                                        MAD11000
      A(MPLUS2)=-HMAX                                                   MAD11010
      RETURN                                                            MAD11020
C     FIND THE INDEX,IMAX,AND VALUE,HIMAX, OF THE LARGEST ABSOLUTE      MAD11030
C     ERROR FOR ALL SAMPLE POINTS                                       MAD11040
   29 A(MPLUS2)=HMAX                                                    MAD11050
      PREVH=HMAX                                                        MAD11060
      IMAX=R(1)                                                         MAD11070
      HIMAX=H                                                           MAD11080
      J=1                                                               MAD11090
```

```
      RJ=R(J)                                                           MAD11100
      DO110 I=1,N                                                       MAD11110
      IF(I.EQ.RJ) GO TO 11                                              MAD11120
      XI=X(I)                                                           MAD11130
      HI=A(MPLUS1)                                                      MAD11140
      K=M                                                               MAD11150
   12 HI=HI*XI+A(K)                                                     MAD11160
      K=K-1                                                             MAD11170
      IF(K-1)112,12,12                                                  MAD11180
  112 HI=Y(I)                                                           MAD11190
      ABSHI=ABS(HI)                                                     MAD11200
      IF(ABSHI.LE.HMAX) GO TO 11                                        MAD11210
      HMAX=ABSHI                                                        MAD11220
      HIMAX=HI                                                          MAD11230
      IMAX=I                                                            MAD11240
      GO TO110                                                          MAD11250
   11 IF(J.GE.MPLUS2) GO TO110                                          MAD11260
      J=J+1                                                             MAD11270
      RJ=R(J)                                                           MAD11280
  110 CONTINUE                                                          MAD11290
C     IF THE MAXIMUM ERROR OCCURS AT A NONREFERENCE POINT, EXCHANGE THISMAD11300
C     POINT WITH THE NEAREST REFERENCE POINT HAVING AN ERROR  OF THE    MAD11310
C     SAME SIGN AND REPEAT                                              MAD11320
      IF(IMAX.EQ.R(1)) RETURN                                           MAD11330
      DO 14 I=2,MPLUS2                                                  MAD11340
      IF(IMAX.LT.R(I)) GO TO 15                                         MAD11350
   14 CONTINUE                                                          MAD11360
      I=MPLUS2                                                          MAD11370
   15 NEXTHI=H                                                          MAD11380
      IF((I-I/2*2).NE.0) NEXTHI=-H                                      MAD11390
      IF(HIMAX*NEXTHI.GE.0) GO TO 115                                   MAD11400
      IF(IMAX.GE.R(1))      GO TO 116                                   MAD11410
      J1=MPLUS2                                                         MAD11420
      J=M                                                               MAD11430
  117 R(J1)=R(J)                                                        MAD11440
      J1=J                                                              MAD11450
      J=J-1                                                             MAD11460
      IF(J-1)118,117,117                                                MAD11470
  118 R(1)=IMAX                                                         MAD11480
      GO TO 2                                                           MAD11490
  116 IF(IMAX.LE.R(MPLUS2)) GO TO 120                                   MAD11500
      J=1                                                               MAD11510
      DO 121 J1=1,MPLUS2                                                MAD11520
      R(J)=R(J1)                                                        MAD11530
  121 J=J1                                                              MAD11540
      R(MPLUS2)=IMAX                                                    MAD11550
      GO TO 2                                                           MAD11560
  115 R(I)=IMAX                                                         MAD11570
```

```
      GO TO 2                                                           MAD11580
  120 R(I-1)=IMAX                                                       MAD11590
      GO TO 2                                                           MAD11600
      END                                                               MAD11610
//GO.SYSIN DD *                                                         MAD11620
LA MESA VILLAGE, 18 AUG 82 0507-0636 LOCAL.                             MAD11630
PSD OF X COIL. AMP IN DB REF NT**2/HZ                                   MAD11640
LA MESA VILLAGE, 18 AUG 82 0507-0636 LOCAL.                             MAD11650
PSD OF Y COIL. AMP IN DB REF NT**2/HZ                                   MAD11660
LA MESA VILLAGE, 18 AUG 82 0507-0636 LOCAL.                             MAD11670
PSD OF Z COIL. AMP IN DB REF NT**2/HZ                                   MAD11680
LA MESA VILLAGE, 18 AUG 82 0507-0636 LOCAL.                             MAD11690
PSD OF TOTAL FIELD. AMP IN DB REF NT**2/HZ                              MAD11700
//GO.FT20F001 DD UNIT=3400-4,VOL=SER=GMDT4A,DISP=(OLD,KEEP),            MAD11710
//             LABEL=(1,NL,,IN),                                        MAD11720
//             DCB=(RECFM=FB,LRECL=32,BLKSIZE=512,DEN=2)                MAD11730
//GO.SYSDUMP DD SYSOUT=A                                                MAD11740
```

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